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TECHNICAL NOTE

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FIXED-BASE-SIMULATOR STUDY OF PILOTED ENTRIES INTO THE EARTH'S ATMOSPHERE FOR A CAPSULE-TYPE VEHICLE AT PARABOLIC VELOCITY

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SUMMARY

This report describes a piloted simulation study relating to entry guidance for a low-lift-drag-ratio vehicle entering the earth's atmosphere at parabolic velocity. Its primary goal was to develop procedures which would allow the pilot to perform the energy-management functions required and to determine the instrument displays needed to aid the pilot in following these procedures. Emphasis was placed on allowing the pilot to make the decisions necessary to assure a safe entry.

Results are presented which illustrate the piloting procedures and instrument displays developed. Included also are the longitudinal and lateral ranges attainable by using these procedures as well as the reaction-fuel requirements associated with the entry conditions covered in the analysis.

The study has indicated that the human pilot with experience and an adequate display of flight information can perform the entry guidance maneuvers required to navigate to a desired destination.

INTRODUCTION

Numerous studies have been made relating to the problem of entry guidance. These studies include automatic- and pilot-controlled entries from circular as well as parabolic velocity. References 1 and 2 present piloted and automatic guidance systems in which longitudinal-range control from circular velocity was achieved by utilizing a reference trajectory which terminated at the desired destination. In reference 3 the reference-trajectory concept was extended to include lateral as well as longitudinal-range control from circular velocity. References 4, 5, and 6 present several possible methods for guiding a vehicle to a desired landing area for entries at parabolic velocity. These references include a piloted simulation study using reference-trajectory techniques, a system employing linear prediction methods, and a repetitive prediction system utilizing rapid-time computer techniques.

In the present study, the problem of guidance from parabolic-entry conditions to a desired point on the earth was investigated further. The study was conducted to develop procedures which would allow a human pilot to perform the energy-management functions required while avoiding the high-deceleration and skip-out regions associated with parabolic entry and to determine the instrument displays required to aid the pilot in following these procedures. Emphasis was placed on allowing the pilot to make the decisions necessary to achieve a successful entry. The instrumentation used was not specialized to entry and, hence, might be used in other phases of a mission.

For trajectory control at subcircular velocity the reference-trajectory, heading-error method of range control, which was studied analytically in reference 3, was modified to utilize the pilot's intelligence and learning capability to supply the guidance logic and control commands. During the period in which the velocity decreased from parabolic to circular, the pilot was given displays to enable him to perform pull-ups which allowed large extensions in range.

In addition to the piloting procedures and instrument displays investigated, several vehicle-parameter studies were made. These included studies of the range attainable for different entry conditions as well as the reaction-fuel requirements and the stagnation-point aerodynamic heating associated with the piloting procedures used in the analysis.

SYMBOLS

In case it is desired to convert distances given to metric units, the following relationships apply: 1 international foot = 0.3048 meter, and 1 international nautical mile = 1.852000 kilometers.

A	orbital heading angle, deg
a_X,a_Y,a_Z	acceleration due to aerodynamic forces along X-, Y-, and Z-axes, respectively, ft/sec^2
a_{Xb},a_{Yb},a_{Zb}	acceleration due to aerodynamic forces along X_b-, Y_b-, and Z_b-axes, respectively, ft/sec^2
b	characteristic span for yawing-moment coefficient, ft
$\bar{c}$	characteristic length for pitching-moment coefficient, ft

C_A	axial-force coefficient
C_m	pitching-moment coefficient
$C_{m,f}$	pitching-moment coefficient due to flap deflection
C_N	normal-force coefficient
C_n	yawing-moment coefficient
$C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$	
C_Y	side-force coefficient
$C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$	
d	diameter of heat shield, ft
F_{Xb},F_{Yb},F_{Zb}	aerodynamic force about X_b-, Y_b-, and Z_b-axes, respectively, lb
g	acceleration due to gravity, ft/sec^2
H	heat absorbed per unit area at stagnation point, Btu/sq ft
h	altitude above surface of earth, ft
I_{Xb},I_{Yb},I_{Zb}	moments of inertia about X_b-, Y_b-, and Z_b-axes, respectively, slug-ft^2
K_q	pitch damping gain, sec^{-1}
K_r	yaw damping gain, sec^{-1}
L/D	lift-drag ratio
L_c	colatitude, deg
m	mass, slugs

p,q,r	angular velocities about X-, Y-, and Z-axes, respectively, radians/sec
q_1,r_1	angular velocities in pitch and yaw due to reaction-control stabilization system and pilot control inputs, radians/sec
$\bar{q}$	dynamic pressure, lb/sq ft
R	range-to-go (great circle distance from vehicle's present position to desired destination), international nautical miles
r	radial distance from vehicle to earth's center, ft
S	frontal surface area, sq ft
t	time, sec
V	velocity, ft/sec
W	weight of vehicle, lb
X,Y,Z	earth-stabilized axes (origin at center of gravity of body); Z-axis is positive toward earth's center and X-axis is positive toward south
X_b,Y_b,Z_b	body axes
X_i,Y_i,Z_i	inertial axes (fixed in space); Z_i-axis is positive toward north
α	angle of attack, deg
β	angle of sideslip, deg
γ	flight-path angle, deg
δ_p	roll-reaction-control input
δ_q	pitch-reaction-control input
ϵ	error, international nautical miles
ϵ_A	error in orbital heading, deg

η	inertial longitude, deg
ρ	atmospheric density, slugs/cu ft
ψ,θ,ϕ	Euler angles, deg

Subscripts:

D	desired destination
L	longitudinal range
l	lateral range
o	value of variable at zero time

Dots above quantities denote differentiation with respect to time.

DESCRIPTION OF SIMULATION

The static simulation of a space vehicle entering the earth's atmosphere at parabolic velocity was performed in a fixed-base cockpit. The vehicle simulated for these tests was of the capsule type with lifting capabilities corresponding to a maximum lift-drag ratio of 0.5. By varying angle of attack and roll angle and hence the magnitude and direction of the lift vector of the vehicle, the pilot was able to control the trajectory.

Equations of Motion

The vehicle was simulated in six degrees of freedom by using the geometry shown in figure 1. The trajectory equations solved in the analysis are derived in reference 2. These equations were simplified by assuming a nonrotating, spherical earth and that entries were made in the equitorial plane. Variations in gravity and in the radial distance from the vehicle to the center of the earth were neglected. The assumed atmosphere was the 1959 ARDC model.

The trajectory equations, moment equations, aerodynamic-force equations, and some auxiliary relationships used in the analysis are given in the appendix. The conventional Euler aircraft angles were obtained by solving the integral Euler angle equations given in the appendix. The stagnation-point, convective-heating-rate formula used in the analysis is of the type used in reference 7 and is also given.

Description of Vehicle

The assumed vehicle was based on the proposed L-2C configuration described in reference 8. The physical characteristics of the vehicle are given in table I. Two possible versions of this vehicle were considered.

Variable L/D vehicle.- One version of the vehicle was assumed to have a capability for varying its lift-drag ratio from 0 to 0.5 by utilizing reaction controls. For this vehicle, the pilot could control motions about the pitch and roll axes. (Pilot control of yaw angle was not considered for either version of the vehicle.)

Control of the trajectory was achieved by regulating the magnitude and direction of the lifting force of the vehicle. The magnitude of the lifting force was determined by the angle of attack. For example, with an angle of attack of 0°, the vehicle produced no lift while with angle of attack set at about 35° the vehicle generated an L/D of 0.5. The direction of the lifting force was regulated by rolling the vehicle. Hence, if maximum lift was desired normal to the flight path (to increase range), the angle of attack was set at 35° and the roll angle at 0°. If maximum lift was desired lateral to the flight path (for heading changes), the angle of attack was maintained at 35° and the vehicle was rolled to a 90° roll angle, whereas if lift was required in a negative direction (to shorten range), the roll angle was increased to 180°. Thus, by varying angle of attack between 0° and 35° and roll angle between 180° and -180° the magnitude and direction of the lift vector could be specified.

Fixed L/D vehicle.- This version of the vehicle was assumed to be pretrimmed at an L/D of 0.5. This trimmed condition could be achieved by utilizing an aerodynamic flap or by offsetting the center of gravity of the vehicle. For this vehicle the pilot had no direct control over angle of attack but could control rolling motions.

Since this version of the vehicle continuously produced a lift-drag ratio of 0.5 only the direction of the lifting force could be controlled. For this vehicle, an effective L/D of zero could be achieved by continuously rolling the vehicle with a constant rolling velocity. However, this maneuver could not be performed in the present analysis since roll angle could be varied only between 180° and -180° because of computing-equipment limitations.

Vehicle Aerodynamics

The assumptions were made that the value of the stability derivatives did not vary with Mach number and that the pitching moment, axial force, and normal force were nonlinear functions of angle of attack. These nonlinear functions are shown in figure 2 along with the corresponding lift and drag curves. The coefficients C_{n_β} and C_{Y_β} were assumed to be constant with values of 0.002 and -0.004 per degree of sideslip, respectively.

It should be stated that the pitching-moment data are for a center of gravity located 0.20d behind the front face and 0.20d above the center line of the vehicle. For the pretrimmed version of the assumed vehicle, the vehicle was balanced at the desired angle of attack by adding a constant increment $C_{m,f}$ to the pitching moment due to angle of attack. This increment was, in effect, a pitching moment due to flap deflection. In practice, the vehicle would probably be balanced by adjusting the center-of-gravity position which would have a slight effect on the shape of the pitching-moment curve.

Reaction-Control and Damping System

A proportional reaction-control and damping system was used for pitch and a nonlinear, on-off control and damping system was used for roll. The attitude-control jets in pitch gave moments which increased linearly with pilot's control deflection. In addition, these jets were assumed to be connected to rate damping systems which produced moments proportional to and opposing angular velocities about the pitch axis. A similar rate damping system was used for damping oscillations in yaw. For the fixed L/D vehicle, of course, the pilot made no control inputs in pitch. A dead spot was included in the on-off roll-control system. For a rolling acceleration of 0.1 radian/sec^2, the dead spot was equivalent to a rolling velocity of about $\pm 5^\circ$ per second or a lateral stick deflection of about $\pm 2.5^\circ$. Thus, if the stick deflection was less than $\pm 2.5^\circ$, the rolling acceleration was zero whereas for greater deflections the rolling acceleration was equal to some preselected value.

The reaction-control stabilization system damped the motions about the body axes of the vehicle. Although it might have been more realistic to have had an on-off control system in pitch and yaw as well as roll, a shortage of computing equipment prevented this.

Standard damping was arbitrarily taken to be that reaction damping which gave a damping ratio of 0.107 in pitch and 0.116 in yaw at maximum dynamic pressure (400 lb/sq ft). Standard damping was used for all tests reported in this analysis except for one series of tests in which the pitch and yaw damping levels were varied. The variation in damping ratio with percent of standard damping is shown in figure 3. It was originally intended that the damping ratio in pitch and yaw should follow the same variation for different levels of damping. However, the yaw damping, as is shown in figure 3, was somewhat higher than the pitch damping because of the fact that an internal servo loop within the computer provided an apparent damping ratio at zero applied damping.

Because of the nature of the stabilization system, the damping ratio and period of oscillation increased as dynamic pressure decreased.

Description of Cockpit and Instrument Display

The layout of the simulated cockpit is shown in the photograph presented in figure 4. The pilot's controls consisted of a side-located fingertip-type controller for pitch and roll. The pilot was also supplied with trim wheels for trimming the vehicle's pitch and roll attitude at any desired value.

The instrument display was intended to provide the pilot with information regarding the attitude and motion of the vehicle and the position and movement of the vehicle with respect to a desired landing area. A drawing of the instrument panel is shown in figure 5.

The instruments include an attitude group consisting of a pitch, roll, and yaw indicator (three-axis "8" ball); and meter-type instruments for angle of attack and sideslip angle. The trajectory variables displayed on instruments included velocity, altitude, vertical velocity, acceleration, and dynamic pressure. In addition the pilot was supplied with instrumentation which would aid him in navigating to a desired destination. This instrumentation is described in following sections of the paper.

Description of Guidance Displays

The instrumentation used primarily for guidance purposes consisted of an x-y recording device on which trajectory variables could be displayed, a cross-pointer type of instrument for showing errors in the vehicle's position and heading with respect to a desired position and heading, and an instrument for displaying the range-to-go of the vehicle from its present position to a desired destination.

x-y recorder.- Because of its versatility and proper size for flight-type instrumentation, the x-y plotter utilized was a cathode-ray type of memory scope. It was located at the bottom of the instrument panel as shown in figure 5. This instrument had a capability for retaining for a long time, information "written" electronically on the face of the display tube. The memory scope was included in the simulation since it provided a flexible type of instrument which could be used in the manner of an x-y plotter for presenting a number of displays to the pilot. The memory scope was mechanized with controls such that at any time during an entry mission the pilot could choose different displays by setting the control switch at the proper position.

The pilot could also "write" prestored references on the memory scope. These stored variations could be retained indefinitely on the memory scope; thus, the pilot was allowed to observe the variation in certain trajectory variables with respect to a precalculated boundary. Switching from one display to another automatically erased the original display from the memory scope. The actual displays available to the pilot are described in the section entitled Pilot Display Studies.

Longitudinal- and lateral-range error instrument.- The previously mentioned cross-pointer instrument presented errors in the vehicle's longitudinal and lateral ranges. These errors were determined in the following manner:

Formulas for the longitudinal and lateral range-to-go and the calculations for desired heading and heading error of the vehicle are given in the appendix and are described in detail in reference 3.

With use of the relations given in the appendix, the error in lateral range was defined by the following equation:

$$\epsilon_l = R \sin \epsilon_A \tag{1}$$

The longitudinal guidance error was determined by the following equation:

$$\epsilon_L = R - R_{reference} \tag{2}$$

The reference range-to-go (similar to concept employed in ref. 3) was calculated for an entry from circular velocity with an initial flight-path angle of -1° at an altitude of 350,000 feet and a constant L/D of 0.2. The actual range-to-go of the vehicle as displayed was simply the resultant of the longitudinal and lateral range-to-go. This range-to-go was somewhat in error for long ranges because of the curvature of the earth but, as the vehicle approached the desired destination, the error was negligible.

The error quantities given in equations (1) and (2) were displayed to the pilot as shown in figure 5. The pilot was also supplied with switches for changing the sensitivity of these error displays. The manner in which the pilot made use of these instruments in controlling the vehicle is described in the section entitled Pilot Procedures Study.

Initial Conditions

In all of the entries discussed some of the initial conditions were the same. The initial altitude was always 400,000 feet and the initial velocity 36,000 ft/sec. The initial entry angles investigated were -5.5°, -6.5°, and -7.5°. Unless otherwise specified the vehicle had standard damping (fig. 3) and a rolling acceleration of 0.1 radian/sec could be commanded.

RESULTS AND DISCUSSION

Pilot Display Studies

The guidance display concept used in this study was to present the pilot with instrument displays which would allow him to perform the energy-management functions required to assure a successful entry. This was done by developing piloting procedures to apply at critical phases of an entry. Displays were then formulated to aid the pilot during these periods. The pilot was supplied with sufficient information at each critical point to review his past maneuvers and to make control decisions based on his present status and the desired destination.

The technique employed in the guidance display studies was to present the pilot with the basic instrumentation described previously (fig. 5) along with different memory-scope displays. The various displays investigated are described in following sections of the paper. The actual piloting procedures used in conjunction with these displays are described subsequently in the section entitled Pilot Procedures Study.

Display for subcircular phase of entries.- Previous studies (ref. 3) have shown that good longitudinal-range control from circular velocity can be achieved by controlling the vehicle to a reference trajectory of range-to-go as a function of altitude which terminates at the desired destination. Hence, it was decided that this method would be utilized for controlling the vehicle's longitudinal range once the velocity of the vehicle was reduced to subcircular values. A display designed for this phase of the entry mission was presented to the pilot on the memory scope. This display used the memory scope as an x-y plotter to show the longitudinal range-to-go of the vehicle as a function of altitude along with the reference trajectory previously described. A drawing of this display is shown in figure 6(a). The outstanding advantage of the memory feature was that it allowed the pilot to correlate his past and present maneuvers so as to provide an almost ideal anticipation of the required control maneuvers. During this subcircular phase of the entry, the pilot used the previously described error instrument for precise control of range-to-go and heading error as the degree of precision in reading absolute error on the scope was not sufficient.

Display for supercircular phase of entries.- During the supercircular phase of an entry, the major areas of concern were deceleration and the possibility of a skip out occurring following the initial plunge into the atmosphere. An accelerometer was found to be adequate for control of deceleration. By knowing the initial rate of descent or by observing the rate of deceleration buildup, the pilot could regulate his lift such as to control his deceleration. For example, on entries with a large initial flight-path angle, it was necessary to apply all lift in an upward direction until the initial deceleration peak was reached; whereas for shallower entries, all lift was not required for deceleration control. A knowledge of the initial flight-path angle was found to be helpful but not necessary since the pilot could estimate his entry angle by observing the rate of the initial deceleration buildup.

Special instrumentation on the memory scope was considered necessary to aid the pilot during the skip-out region of the entry. This skip-out region occurs during any pull-up at supercircular velocities following the initial entry into the earth's atmosphere. These pull-ups are necessary to remove the vehicle from the dense atmosphere when long ranges are required.

A memory-scope display, provided during the skip-out region, showed the vertical velocity of the vehicle as a function of altitude along with a precalculated boundary. This display is presented in figure 6(b). At points along the boundary, the centrifugal force of the vehicle could just be overcome by its lifting force assuming that the lift is applied downward. This trace was established by computing maximum-negative-lift trajectories for the vehicle which arrived at an altitude of 250,000 feet with no vertical velocity. Although these final conditions could be satisfied for a wide range of final velocities, it was determined that the altitude—vertical-velocity profiles were essentially the same for final velocities between 25,000 ft/sec and 30,000 ft/sec. The actual trace presented on the scope was for a velocity of 30,000 ft/sec at an altitude of 250,000 feet. An altitude of 250,000 feet was chosen since the dynamic pressure at this altitude is low enough to prevent the vehicle from slowing down too rapidly, but sufficient to allow control of the vehicle's trajectory.

No attempt was made to refine the instrument panel to obtain an optimum display in this study. However, the results indicate that the information supplied to the pilot was sufficient to allow him to assess his situation at any point during the entry and to decide what maneuvers he must make to accomplish a successful entry for the entry conditions covered in the analysis.

Pilot Procedures Study

For any safe entry condition, there is a wide range of possible landing areas, depending upon the maneuvers performed by the pilot during the entry. In the present study the pilot supplied the control logic for determining the entry maneuvers and hence it was necessary to develop procedures to aid the pilot in performing the energy-management functions properly. These procedures were intended to provide the pilot with locations along the trajectory at which he should arrive with a predetermined range of values of velocity, altitude, and vertical velocity. It was found that the pilot could perform these procedures correctly, make efficient use of the energy of the vehicle, and arrive at the desired destination.

The results presented are representative of a pilot proficient in the operation of the simulator and with a thorough understanding of the proposed operation of the simulated vehicle.

Range procedure.- For simplicity, the vehicle's total range capability was divided into three general regions: short, medium, and long ranges. The short ranges included those less than 2,000 miles. The medium ranges were between 2,000 and 4,000 miles and long ranges were those greater than 4,000 miles. The piloting procedures for each of these regions are described in general terms with the aid of the typical piloted entries shown in figure 7. Detailed descriptions of certain phases of the mission such as the pull-up maneuver, lateral maneuver, and terminal maneuver are given in subsequent sections of the paper. For the entries shown in figure 7 the pretrimmed version of the vehicle was used and the initial entry angle was -6.5°. This entry angle is at about the center of the safe entry corridor. The piloting procedure naturally varied somewhat with initial entry angle as is explained in a subsequent section of the paper.

Short-range entries (2,000 miles or less).- For short-range entries, the piloting procedure consisted of a pull-out at an altitude of about 200,000 feet followed by a coasting period at or near this altitude and a final descent along the reference trajectory to the desired destination. The primary navigation instruments for these entries were those showing altitude plotted against range-to-go (fig. 6(a)), range-to-go, and heading error, and the accelerometer. By observing on the memory scope the vehicle's position with respect to the reference trajectory, the pilot could maintain his deceleration at levels such that he would intersect the reference trajectory with the required energy to allow a descent along the reference trajectory. Thus, for desired ranges near the lower limit of the vehicle's range capability the pilot was required to attain and maintain a near-maximum deceleration for a major portion of the entry. An additional task for these entries as for all entries was to obtain and maintain the desired heading by utilizing available lift in the lateral direction.

Time histories for a typical short-range entry are shown in figure 7(a). The variation in longitudinal range-to-go with altitude and with lateral range-to-go for this entry is shown in figure 7(d). For this entry the desired longitudinal range was 1,500 miles and the desired lateral range was 200 miles.

Figures 7(a) and 7(d) show that the pilot leveled off at an altitude slightly below 200,000 feet and maintained this altitude until the longitudinal guidance error was reduced to zero (at $t = 290$ seconds) and then began a descent along the reference trajectory. Figure 7(a) shows that as the dynamic pressure began to build up, the pilot rolled the vehicle to an attitude of -45° to start correcting the heading error. As the deceleration reached its peak value of about 6g, the pilot rolled to -90° to direct all of the lift in a lateral direction to further correct the heading error and to prevent a pull-up. He maintained the roll angle near -90° until the error in lateral range-to-go was reduced to zero and then varied the roll angle between 90° and -90° to maintain the heading and longitudinal range-to-go errors near zero. The initial increase in the longitudinal guidance error results from the fact that the vehicle's flight-path angle is greater than the reference trajectory's flight-path angle.

Shown also in figure 7(a), along with the basic trajectory variables, is the aerodynamic heat input and the roll and yaw reaction-fuel parameters. A discussion of these quantities is given in a subsequent section of the paper.

<u>Medium-range entries (2,000 to 4,000 miles)</u>.- The piloting procedure for these entries was similar to that for short ranges during the initial portion of the entry. The pilot would level off at an altitude of about 200,000 feet and maintain this altitude until the velocity dropped below a predetermined value (28,000 and 30,000 ft/sec). This was done to dissipate energy and to reduce the possibility of skipping back out of the earth's atmosphere. The pilot would then initiate a rate of climb and by observing the vehicle's trace on the altitude—vertical-velocity display (fig. 6(b)) would regulate his lift so as to keep the vehicle's trace just inside the reference trace. Thus, the vehicle would arrive at an altitude of 250,000 feet with a near-circular velocity and a flight-path angle of zero. The pilot would then maintain this altitude until the vehicle intersected the reference trajectory. For these medium-range

entries, the pilot made use of the altitude—vertical-velocity display during the supercircular phase of the entry and the altitude—range-to-go display during the circular and subcircular phase.

A typical medium-range entry is illustrated in figures 7(b) and 7(d). For this entry the desired longitudinal range was 3,500 miles and the desired lateral range was 300 miles.

Figures 7(b) and 7(d) show that the pilot leveled off at an altitude of about 200,000 feet and maintained this altitude until the velocity was reduced to about 30,000 ft/sec. He then began to pull-up at $t = 90$ seconds, and at $t = 140$ seconds he rolled the vehicle to -180° to level off at an altitude of 250,000 feet at which point his velocity was 25,000 ft/sec. The timing required during this pull-up maneuver was not found to be too critical. For example, as long as the pull-up velocity was within the range between 28,000 to 30,000 ft/sec, the mission could be accomplished. A more complete discussion of the pull-up maneuver is given in a subsequent section of the paper.

After leveling off at 250,000 feet, the lateral-range error was small so the pilot reduced the roll angle to zero to direct all of the lift in an upward direction and began a coasting phase to the reference trajectory. At $t = 500$ seconds, the pilot observed that the lateral-range error was increasing slightly so he rolled the vehicle to reduce this error somewhat. At $t = 680$ seconds, the longitudinal guidance error was reduced to zero so the pilot varied his roll angle to maintain this error and the heading error near zero during the descent to the desired destination.

Long-range entries (greater than 4,000 miles).- For long-range entries, the pilot initiated a pull-up immediately after the vehicle leveled off in order to remove the vehicle from the dense portions of the atmosphere as rapidly as possible and hence retain as much of the vehicle's initial energy as possible. He then used the altitude—vertical-velocity display to insure that the vehicle would not skip back out of the earth's atmosphere. For these entries it was critical that the pilot keep his vehicle's trace below the reference trace or there was a great danger that he would lose control of the vehicle's trajectory and, hence, proceed into an uncontrolled elliptical orbit about the earth.

By executing properly the previously described procedure, the vehicle would arrive at an altitude of 250,000 feet in a level attitude and with supercircular velocity (28,000 to 30,000 ft/sec). At this time a gradual ascent was begun to allow the vehicle to reach an altitude of about 300,000 feet from which a coasting phase to the reference trajectory could begin. The atmosphere has little density at these altitudes and hence the vehicle could traverse long ranges with little reduction in velocity for these conditions. This climbout to 300,000 feet was a critical phase of the mission since the vehicle was traveling at supercircular velocity much of the time and the danger of a skip out existed. However, by maintaining the vertical velocity at small values (about 100 ft/sec) control of the trajectory could be achieved throughout the maneuver. The temporary "pause" at an altitude of 250,000 feet was made to assure that the pilot had control over his vehicle's trajectory before proceeding into less dense atmosphere.

A typical long-range entry is shown in figures 7(c) and 7(d). For this entry, the desired longitudinal range was 6,000 miles and the desired lateral range was 400 miles.

For this entry, the pilot made an immediate pull-up and at $t = 100$ seconds rolled inverted to level off at an altitude of 250,000 feet at which point his velocity was about 28,000 ft/sec. The pilot then established a rate of climb of about 100 ft/sec and reached a maximum altitude of 280,000 feet where his velocity was nearly 26,000 ft/sec. During the ascent to maximum altitude, it was necessary to maintain a roll angle greater than 90° since the vehicle was traveling at velocities greater than circular velocity. If, during this period, the pilot had directed the lift of the vehicle in an upward direction for a short period of time, a skip out would have occurred.

As the vehicle reached its maximum altitude, the pilot reduced the roll angle and began a coasting period to the reference trajectory. At $t = 1,100$ seconds, the vehicle intersected the reference trajectory and a descent was begun to the desired destination. Note that the dynamic pressure and hence deceleration was very small throughout much of the entry because of the high-altitude coasting phase.

During the initial phase of all entries, the pilot made little use of the longitudinal-guidance-error instrument, since the initial pull-up maneuvers were determined by the desired landing point. By observing the range-to-go meter, the pilot could tell when he was in the vicinity of the reference trajectory and could then utilize the longitudinal guidance error to guide the vehicle onto the reference trajectory.

The piloting procedures have been described in terms of long-, medium-, and short-range entries. There is, of course, an overlapping between the three range procedures. For example, on an entry with a desired range at the lower end of the medium-range regime, the pilot might use the following method. Rather than pull-up to an altitude of 250,000 feet and begin an immediate descent, the pilot might level off at an altitude of 230,000 feet and make a more gradual descent to the desired destination.

Variation in piloting procedures with entry angle.- The previously described piloting procedures were for entries at an initial entry angle of -6.5°. The piloting procedures naturally varied somewhat with initial entry angle since for different entry angles the initial pull-up is made at different altitudes. Thus, for steep entry angles, all lift was applied in an upward direction initially to prevent excessive deceleration; whereas for shallow entry angles, lift was applied in a downward direction initially to "pull" the vehicle into the atmosphere. The shallow entry angles were actually more desirable from the piloting standpoint as rapid pull-ups were not necessary since the vehicle tended to level off at higher altitudes following the initial plunge into the atmosphere. Following the initial pull-up, the coasting and final descent phase of an entry was the same for all entry angles.

Pull-up procedure.- A properly executed pull-up maneuver and one for which a skip out occurred are illustrated in figure 8. The trajectories shown in figure 8 are for a long-range entry in which the pilot made an immediate pull-up and then attempted to level off at an altitude of 250,000 feet. Presented in figure 8 are the roll angle and altitude as functions of time along with the altitude—vertical-velocity profile as displayed to the pilot on the memory scope.

Figure 8 shows that as the pull-up began and vertical velocity approached 800 ft/sec, the pilot slowly rolled the vehicle to reduce the upward lift component in order to maintain his rate of ascent at about 800 ft/sec. For the case where a safe pull-up was achieved, the pilot rolled inverted as the vehicle approached the reference trace (about 5,000 feet below reference) and controlled his trajectory such that it remained under the reference trace. Thus, the vehicle arrived at an altitude of 250,000 feet with a zero flight-path angle and a velocity of about 29,000 ft/sec.

For the entry where a skip out occurred, the pilot did not initiate the final roll maneuver until his vehicle was within about 1,000 feet of the reference trace. Hence, the vehicle had crossed the reference trajectory before the lift vector had been completely directed in a downward direction. Thus the centrifugal force exceeded the gravitational force and a skip out occurred.

The roll-angle time history in figure 8 shows that no rapid rolling maneuvers were necessary to safely control the vehicle's trajectory. The most critical phase of the maneuver was to maintain the rate of ascent at about 800 ft/sec and then to direct the lift of the vehicle downward before the vehicle reached the reference altitude. However, since these events occur over a relatively long period of time, the pilots had no difficulty in providing the anticipation required to perform the necessary maneuvers. Of importance here is the fact that pilot anticipation is substituted for rapid rolling maneuvers.

The pull-up procedure for shorter ranges is identical to the previously described maneuver except the pilot's margin for error is greater for shorter entries since the vehicle is traveling at lower velocities which reduces the danger of a skip out.

Lateral-maneuver procedure.- The lateral-maneuver procedure depended somewhat on whether the pretrimmed or variable L/D version of the vehicle was used. For both vehicles, the initial maneuver was the same and was made during the high-deceleration period associated with the initial plunge into the atmosphere. During this period, all lift which was not needed in controlling the deceleration and longitudinal range was used in a lateral direction for heading changes. Heading changes are naturally more effective early in the entry since the lateral component of velocity introduced can act over a longer period of time thus resulting in greater lateral range. The effect of rolling to obtain a side component of lift during the initial skip is shown in figure 7(d). For all three entries shown in this figure, the vehicle obtained its proper heading early in the entry and only small heading corrections were required throughout the remainder of the entry.

After the initial pull-up, the lateral maneuvers depended on the assumed vehicle. For the variable L/D vehicle, the maneuvers were simplified since lateral- and longitudinal-range control maneuvers could be made somewhat independently. Hence, once the correct heading was acquired, the lateral component of lift could be removed ($\phi = 0^{\circ}$) and the longitudinal range could be controlled by varying angle of attack. As was shown in reference 3, only minor corrections are required to maintain the proper heading once it has been established.

Maintaining a desired heading required more concentration by the pilot for the pretrimmed vehicle since only the direction of the lift vector could be specified and the lift of the vehicle had to be continuously proportioned between the lateral and longitudinal planes. Hence, it was necessary to zigzag about the correct heading and to anticipate when the vehicle should be rolled to change the direction of the lift vector. This procedure is shown in figure 7(a). For this entry, the lateral-range error was first reduced to zero at $t = 140$ seconds. The pilot allowed the error to build up for a period of time and then, at $t = 170$ seconds, he rolled the vehicle to begin correcting the lateral-range error. This time lag in correcting the heading error was reduced as the vehicle approached the desired destination so as to damp out oscillations about the desired heading. The lateral maneuvers required with the pretrimmed vehicle presented no problems to an experienced pilot and, in fact, the pretrimmed vehicle was preferred to the variable L/D vehicle by most pilots since it required control of the vehicle about only one body axis. In general, the pilots preferred to pretrim the variable lifting vehicle at an L/D of 0.5 and to maintain this angle of attack until the heading error was reduced to zero and/or the descent along the reference trajectory was begun.

Terminal-control procedures.- Terminal control of the vehicle along the reference trajectory depended on the assumed vehicle in the same manner as in the lateral maneuvers. For the variable L/D vehicle, the pilot maintained his longitudinal guidance error near zero by varying the angle of attack of the vehicle and hence lift and controlled his lateral-range error in the manner described in the previous section. For the pretrimmed vehicle, the pilot had to coordinate his roll maneuvers so as to simultaneously control the longitudinal- and lateral-range errors and bring them to zero at the desired destination.

In general, the piloting procedure used in the terminal descent involved reducing the longitudinal guidance error to zero while establishing a rate of descent which approximated that of the reference trajectory (-400 to -600 ft/sec). Then by observing the error instruments and by using the vertical-velocity instrument and the memory-scope display to help supply anticipation, the pilots were able to maintain the longitudinal- and lateral-range errors near zero.

The final errors in longitudinal range and lateral range for several entries are shown in figure 9. This figure presents a comparison of the terminal errors for entries in which the pilot had roll-only control and roll-pitch control. The figure shows the magnitude of the errors at an altitude of 100,000 feet above the desired destination. Figure 9 shows that in all cases the final errors were less than 10 miles. For the roll-only control (pretrimmed vehicle) the final errors in lateral range were generally larger than for the roll-pitch control because of the necessity of oscillating about the desired heading.

Improvements in the display such as supplying anticipation in the error instruments might have reduced the final errors. However, the errors shown in figure 9 were nearing the resolution limits of the instrumentation used and, hence, any major reduction in the final errors would have required more accurate equipment.

One factor which definitely complicated the piloting problem and probably contributed to the terminal errors was the previously mentioned roll limitation. Since the vehicle could not be rolled through the 180° position, it was necessary to roll the vehicle through 0° to change the direction of the lift vector. For example, if the vehicle were at a roll angle of 170° and a roll angle of -170° was desired, it was necessary to roll the vehicle through 340° rather than the much shorter 20° which would be required if the computing equipment permitted unlimited rolling of the vehicle.

Vehicle-Parameter Studies

Studies were made of the range capability, aerodynamic heat input, and reaction-fuel requirements associated with the piloting procedures used during entry into the earth's atmosphere.

Range capability.- The maximum range capability for three initial entry angles is shown in figure 10. These contours represent a locus of the end points of trajectories showing the area in which the vehicle could be controlled to within 10 miles of the desired destination at an altitude of 100,000 feet above the destination. Limitations placed on the development of these range contours were that the vehicle's deceleration should never exceed 10g and that the vehicle should never climb above an altitude of 300,000 feet during the guidance phase of the entry.

As was shown in reference 4, figure 10 shows that the range capability is increased as the entry angle is decreased. This result is obtained because the maximum deceleration during the initial plunge into the atmosphere is reduced as entry angle is reduced. Hence, more of the initial energy of the vehicle can be retained for shallow entries. The minimum range capability is decreased slightly as the entry angle is increased since the maximum deceleration can be reached sooner for large initial entry angles than for small ones.

Figure 10 shows that for ranges up to about 4,000 miles, the maximum lateral range attainable is larger for an entry angle of -6.5° than for the -5.5° and -7.5° entries as was also shown in reference 4. This result occurs because, for the -6.5° entry, some of the lifting capability of the vehicle can be used for heading changes throughout the entry whereas for steeper entries the lift must be applied in an upward direction during most of the pull-up to prevent overdecelerating the vehicle. For the shallow entries the lift must be initially applied in a downward direction to prevent a skip out.

The exact shape of the rahge-capability contour at the maximum-range end of figure 10 is hard to define. There may be computer inaccuracies present due to the long times required for these entries and due to the fact that during many of these entries the vehicle is flying near the skip-out boundary and hence nearly equal quantities are being subtracted in the computer (centrifugal force and gravitational plus lifting force). However, for the present computer setup, the contour shown in figure 10 should be representative of the range capability of the assumed vehicle.

The method of trajectory control (roll-pitch or roll-only) had no effect on the range capability of the vehicle, because for both vehicles the maximum lifting capability could be employed if necessary throughout the entry. For short, straight-ahead entries, the variable L/D vehicle was somewhat easier to maneuver inasmuch as the upward lift component could be reduced without rolling the vehicle and thereby changing the heading.

Aerodynamic heat input.- The stagnation-point, convective-heat inputs for several entries with different desired ranges are shown in figure 11. This figure also shows a comparison between the total heat input for direct entries (such as those investigated in this paper), and for skip entries in which the desired range was acquired by allowing the vehicle to skip out of the earth's atmosphere on a trajectory which would reenter near the desired destination. The total-heat-input calculations considered only the contribution due to aerodynamic heating at the stagnation point and did not include such effects as radiative heating. The stagnation point was considered to be the spherical edges of the heat shield and a radius of curvature of 1 foot was assumed. The results shown in figure 11 were for an entry angle of -6.5°.

The skip entries were accomplished by a trial-and-error method. The lift of the vehicle was varied such that it initially leveled off at an altitude which gave a deceleration of about 6g. This altitude was maintained until the velocity reached a certain value and then maximum lift was applied in an upward direction causing the vehicle to skip out of the earth's atmosphere. The vehicle then followed a ballistic path, and after entry the lift was regulated in such a manner that the vehicle could descend along a reference trajectory. This method was repeated for different pull-up velocities until the desired ranges were obtained. This procedure resulted in an initial rapid-deceleration period followed by a slow rise out of the atmosphere and a gradual descent back into the atmosphere.

Figure 11 shows that for direct entries, the heat input increases almost linearly with desired range. This figure also shows that for ranges greater than about 4,000 miles, the heat input is greater for direct entries than for skip entries. An explanation of this fact, as reported in reference 7, is that during the constant-altitude (near constant deceleration) slow-up phase of the skip entry the vehicle maintains the highest Reynolds number consistent with the load limit and hence the lowest ratio of friction to pressure drag. The actual lower boundary for the total heat load would be provided by a constant maximum-deceleration slow-up. (See ref. 7.)

Some typical heating time histories are shown in figure 7 for different desired ranges.

Reaction-Fuel Requirements

An investigation was made to determine some reaction-fuel requirements for the pretrimmed version of the simulated vehicle with an initial entry angle of -6.5°. The results are presented in figure 12 in a manner such that they could be applied to a vehicle having different physical characteristics than those of the proposed vehicle and are described in the following sections of the paper. A quantity defined as the reaction-fuel parameter is compared for different desired ranges, level of artifical damping applied, and rolling accelerations. The reaction-fuel parameter about each body axis is just the integral with respect to time of the magnitude of the angular acceleration about each axis produced by the reaction-control stabilization system and pilot control inputs. The total reaction-fuel parameter is the sum of each contribution $\left(\text{total reaction-fuel parameter} = \int |\dot{p}| dt + \int |\dot{q}_1| dt + \int |\dot{r}_1| dt\right)$. Thus, by assuming a lever arm and a specific impulse, the quantity of reaction fuel could be computed from the reaction-fuel parameter.

The proportional control system in pitch and yaw and the off-on system in roll which were assumed in the present analysis and which would be contributing factors to the reaction-fuel parameter were described in a previous section. The computed reaction-fuel quantities result from pilot control inputs as well as from the automatic stabilization system. It should be stated that the pilot was not given a fuel indicator and did not attempt to conserve fuel within any specified limit. He merely made the maneuvers required to accomplish a successful entry.

Variation in reaction-fuel parameter with range.- A summary plot showing the variation in the reaction-fuel parameter with desired range is given in figure 12(a). For the entries presented in this figure, the vehicle was assumed to have standard damping in pitch and yaw (fig. 3) and a rolling acceleration of 0.1 radian/sec. Various lateral ranges within the range capability of the vehicle are included in the data shown in figure 12(a).

Figure 12(a) shows that the reaction-fuel parameter varied almost linearly with the desired range with a slope of about 3.5 radians/sec per 1,000 miles of desired range.

Of interest are the individual contributions to the reaction-fuel parameter due to motions about the separate body axes. It was found that the roll-reaction-fuel parameter increased only slightly with desired range with the average contribution being about 7 radians/sec. This result is shown in the examples shown in figure 7 since for ranges between 1,500 and 6,000 miles the roll-reaction-fuel parameter varied only between about 6 radians/sec and 9.5 radians/sec. This relatively constant usage of roll reaction fuel resulted since the rolling maneuvers required were about the same regardless of the desired range.

The reaction fuel required for pitch and yaw damping was found to increase more rapidly with range than roll reaction fuel as would be expected since for longer ranges the entry time was increased and more damping maneuvers were required. Since the average contribution due to roll was about 7 radians/sec, the remainder of the reaction-fuel parameter for any range shown in figure 12(a) was due to pitch and yaw damping with about 80 percent due to yaw damping and about 20 percent due to pitch damping. Of significance is the fact that with the assumed control system, it was found that the contribution due to yaw damping formed a major portion of the total reaction-fuel parameter shown in figure 12(a). In this figure, the yaw-reaction-fuel parameter varied between 8 radians/sec and 18.5 radians/sec for desired ranges of 1,500 miles and 6,000 miles. The sideslip-angle trace in figure 7 shows why large quantities of fuel were required for yaw damping. For the assumed vehicle, rolling maneuvers about the body axis with an angle of attack of 35° cause the vehicle to yaw and the resulting oscillations in this yaw angle were damped out by the assumed stabilization system. Smaller oscillations also occur in angle of attack as shown in figure 7.

The large yaw-damping-fuel usage suggests that the damping level was too high or that the assumed control system made an inefficient use of the reaction fuel. A lower damping level at high-dynamic-pressure conditions or damping about axes other than the body axes might reduce the fuel requirements. Another possibility would be to apply roll torques about axes other than the body axes. A change in the inertia distribution of the vehicle would also affect the reaction-fuel requirements.

Variation in reaction-fuel parameter with vehicle damping.- The variation in the reaction-fuel parameter with artifical damping applied about the pitch and yaw body axes is shown in figure 12(b) for several entries. For these entries, the desired range was 2,800 miles and the rolling acceleration was 0.1 radian/sec.

In figure 12(b), the average contribution due to roll remained at about 7 radians/sec since the damping was applied only in pitch and yaw. The breakdown on the remainder of the reaction fuel at any damping level remained about the same as in figure 12(a), 80 percent for yaw damping and 20 percent for pitch damping. For example, with 50 percent of standard damping, the average contributions were as follows: 7 radians/sec due to roll, 7 radians/sec due to yaw damping, and 2 radians/sec due to pitch damping.

Variation in reaction-fuel parameter with rolling acceleration.- The variation in the reaction-fuel parameter with the vehicle's rolling acceleration is given in figure 12(c) for several entries with a desired range of about 1,400 miles. For these entries the vehicle was assumed to have standard damping in pitch and yaw. Figure 12(c) shows that the reaction-fuel requirements increase only slightly with increases in the rolling acceleration. This result occurred since for higher rolling accelerations the pilot could obtain a desired roll angle by applying a control input for a shorter period of time.

Although no attempt was made to determine the effect of rolling acceleration on terminal errors, it is reasonable to assume that higher rolling accelerations would allow the pilot to make corrections in longitudinal and lateral range quicker and possibly reduce the terminal errors in these quantities. The pilots generally preferred rolling accelerations from 0.2 to 0.3 radian/sec^2.

Minimum Display Requirements

Some consideration was given to the formulation of a minimum guidance display which would still allow the pilot to perform the navigation functions described in previous sections of the report. This was done by blocking off certain instruments and using the remaining instruments for range control. These studies were carried out by using the pretrimmed version of the vehicle with standard damping about the pitch and yaw axes, a rolling acceleration of 0.1 radian/sec^2, and an initial entry angle of -6.5°. These studies were made after the pilots had become thoroughly familiar with the operation of the simulator.

It was found that for entries with desired ranges less than about 4,000 miles, the pilots could perform the required entry maneuvers and arrive at the desired destination without using the memory-scope displays. Extreme caution had to be exercised during the supercircular phase of these entries to assure that no skip out occurred during the initial pull-up. The pilots would generally perform the pull-up and then roll the vehicle to level off at a lower altitude than if the altitude—vertical-velocity display had been used. This maneuver gave a larger margin for error and still allowed the desired destination to be reached since once the skip out had been controlled, the pilots could climb to a less-dense altitude if necessary. During the subcircular phase of these entries the pilots made use of the longitudinal- and lateral-range-error instrument for guiding onto the reference trajectory. Descents along the reference trajectory by using this error instrument were relatively easy for the experienced pilot.

For ranges greater than 4,000 miles, where the skip-out problem was most pronounced, the piloting was much more difficult without the altitude—vertical-velocity display. The pull-up and leveling-off maneuver at supercircular velocity could be achieved, however, by rolling the vehicle inverted at a predetermined altitude during the pull-up. A warning light to tell the pilot when to make this rolling maneuver would have been very helpful.

The basic instruments required by the pilots in guiding the vehicle to any point within the range capability of the vehicle were those which indicated the longitudinal- and lateral-range errors, velocity, altitude, vertical velocity, acceleration, roll angle, and position of the vehicle with respect to a skip-out boundary. The three-axis "8" ball gave the pilots a good physical feeling as to the orientation of the vehicle, but was not actually needed and could have been replaced by a roll-angle meter. Both angle of attack and sideslip angle were unnecessary for the pretrimmed vehicle. Of course, angle of attack would be needed for the variable L/D vehicle. The dynamic-pressure instrument was not used by the pilot as the acceleration meter gave sufficient information in this respect. A reaction-fuel meter would probably have been desirable.

For entries in which no pull-up was required (range of less than 2,000 miles) the pilot could navigate to the desired destination by using only the error instrument and the deceleration and roll-angle instruments. For these entries, the pilot would acquire and maintain a deceleration level which would allow him to intersect the reference trajectory with the required energy to allow a descent to the desired destination. For example, with desired ranges at the lower limit of the vehicle's range capability the pilot would maintain a near-maximum deceleration until the range errors were reduced to zero whereas, for longer ranges, he would maintain lower levels of deceleration. By maintaining the deceleration at high levels, the pilot could remove the skip-out problem and by observing the rate of change of deceleration, the pilot could obtain information about his vertical velocity. For example, if the deceleration were increasing, the pilot would know he was descending whereas, if the deceleration was about constant or decreasing slightly, he would know he was maintaining a near-constant altitude. However, if the deceleration decreased more rapidly, he knew he was climbing into a less-dense atmosphere.

It should be emphasized that to perform the navigation functions by using these reduced instrument displays required considerable experience in the operation of the simulator and a thorough understanding of the problem by the pilots. The pilot was, in effect, able to estimate such missing quantities as altitude and velocity at different points along the trajectory because of the experience acquired in flying numerous entries and from observing the variations in these quantities.

SUMMARY OF RESULTS

The results of a simulation study of piloted entries into the earth's atmosphere for a capsule-type vehicle at parabolic velocity can be summarized as follows:

1. The study has indicated that the human pilot with experience and an adequate display of flight information can perform the entry guidance maneuvers required to navigate to a desired destination. The instrument display required depended upon the mission. For example, with long-range entries which required pull-ups at superorbital velocities the information display included the following: vehicle attitude, basic trajectory variables, distance from the desired destination and heading with respect to the desired destination, and an indication of the vehicle's position with respect to a skip-out boundary. For ranges near the lower limit of the vehicle's capability, the mission could be accomplished with the following instrument displays: roll angle, deceleration, distance from the desired destination, and heading with respect to the desired destination.

2. There was no significent difference in the range capability of the variable L/D vehicle (pitch-roll control) and the pretrimmed vehicle (roll only control). The final errors in cross range were generally smaller for the variable L/D vehicle than for the pretrimmed version of the vehicle. However, for both vehicles, the final range errors were always less than ±10 nautical miles.

3. The reaction fuel required for roll control and for pitch and yaw damping about the principal body axes was found to vary almost linearly with desired range. The reaction fuel required for yaw damping was found to be about four times that required for pitch damping. It was found that the reaction fuel used for roll control during an entry increased only slightly with increases in the assumed rolling acceleration of the vehicle.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 9, 1962.

APPENDIX

EQUATIONS OF MOTION USED IN SIMULATION

The equations of motion and guidance geometry used in the present analysis are presented herein. Earth-stabilized-axes force equations:

$$\ddot{L}_c = \frac{a_X}{r} - \frac{2\dot{h}\dot{L}_c}{r} + \dot{\eta}^2\left(\frac{\pi}{2} - L_c\right)$$

$$\ddot{\eta} = \frac{-a_Y}{r}\,\frac{-2\dot{h}\dot{\eta}}{r} - 2\dot{\eta}\dot{L}_c\left(\frac{\pi}{2} - L_c\right)$$

$$\ddot{h} = -a_Z + r\left(\dot{L}_c{}^2 + \dot{\eta}^2\right) - g$$

Body-axis moment equations:

$$\dot{p} = f\left(\delta_p, p\right)$$

$$\dot{q} = \left[C_m(\alpha) + C_{m,f}\right]\frac{\bar{q}S\bar{c}}{I_{Yb}} + rp\,\frac{I_{Xb} - I_{Zb}}{I_{Yb}} + K_q q + f\left(\delta_q\right)$$

$$\dot{r} = C_{n_\beta}\beta\,\frac{\bar{q}Sb}{I_{Zb}} + pq\,\frac{I_{Yb} - I_{Xb}}{I_{Zb}} + K_r r$$

Aerodynamic-force equations:

$$\frac{F_{Xb}}{m} = C_A(\alpha)\,\frac{\bar{q}S}{m} = a_{Xb}$$

$$\frac{F_{Yb}}{m} = C_{Y_\beta}\beta\,\frac{\bar{q}S}{m} = a_{Yb}$$

$$\frac{F_{Zb}}{m} = -C_N(\alpha)\ \frac{\bar{q}S}{m} = a_{Zb}$$

Euler angle relationships:

$$\dot{\phi} = p + \dot{\psi} \sin \theta$$

$$\dot{\theta} = q \cos \phi - r \sin \phi$$

$$\dot{\psi} = \frac{r \cos \phi + q \sin \phi}{\cos \theta}$$

$$\alpha = (\theta + \gamma)\cos \phi + (\psi - A - 180^{\circ})\sin \phi$$

$$\beta = (\psi - A - 180^{\circ})\cos \phi - (\theta + \gamma)\sin \phi$$

Auxiliary relationships:

$$V = \left[r^2\left(\dot{L}_c{}^2 + \dot{\eta}^2\right) + \dot{h}^2\right]^{1/2}$$

$$\gamma = \frac{\dot{h}}{V}$$

$$A = \tan^{-1}\left(\frac{\dot{L}_c}{\dot{\eta}}\right) - \frac{\pi}{2}$$

$$\dot{H} = 2 \times 10^{-8}\left(\rho^{1/2}V^3\right)$$

Guidance geometry:

$$R_L = \eta_D - \eta$$

$$R_l = L_{c,D} - L_c$$

$$R = \left(R_L{}^2 + R_l{}^2\right)^{1/2}$$

$$A_D = \tan^{-1}\left(\frac{R_l}{R_L}\right) - \frac{\pi}{2}$$

$$\epsilon_A = A_D - A$$

REFERENCES

1. Assadourian, Arthur, and Cheatham, Donald C.: Longitudinal Range Control During the Atmospheric Phase of a Manned Satellite Reentry. NASA TN D-253, 1960.

2. Cheatham, Donald C., Young, John W., and Eggleston, John M.: The Variation and Control of Range Traveled in the Atmosphere by a High-Drag Variable-Lift Entry Vehicle. NASA TN D-230, 1960.

3. Young, John W.: A Method for Longitudinal and Lateral Range Control for a High-Drag Low-Lift Vehicle Entering the Atmosphere of a Rotating Earth. NASA TN D-954, 1961.

4. Foudriat, Edwin C., and Wingrove, Rodney C.: Guidance and Control During Direct-Descent Parabolic Reentry. NASA TN D-979, 1961.

5. Wingrove, Rodney C., and Coate, Robert E.: Piloted Simulator Tests of a Guidance System Which Can Continuously Predict Landing Point of a Low L/D Vehicle During Atmosphere Re-Entry. NASA TN D-787, 1961.

6. Sommer, Simon C., and Short, Barbara J.: Point Return From a Lunar Mission for a Vehicle That Maneuvers Within the Earth's Atmosphere. NASA TN D-1142, 1961.

7. Grant, Frederick C.: Simple Formulas for Stagnation-Point Convective Heat Loads in Lunar Return. NASA TN D-890, 1961.

8. Rainey, Robert W., compiler: Summary of Aerodynamic Characteristics of Low-Lift-Drag-Ratio Reentry Vehicles From Subsonic to Hypersonic Speeds. NASA TM X-588, 1961.

TABLE I

INERTIA, WEIGHT, AND DIMENSIONS FOR SIMULATED VEHICLE

I_{Xb}, slug-ft^2	918
I_{Yb}, slug-ft^2	1,141
I_{Zb}, slug-ft^2	1,143
b, ft	11.6
$\bar{c}$, ft	11.6
W, lb	6,500
S, sq ft	106

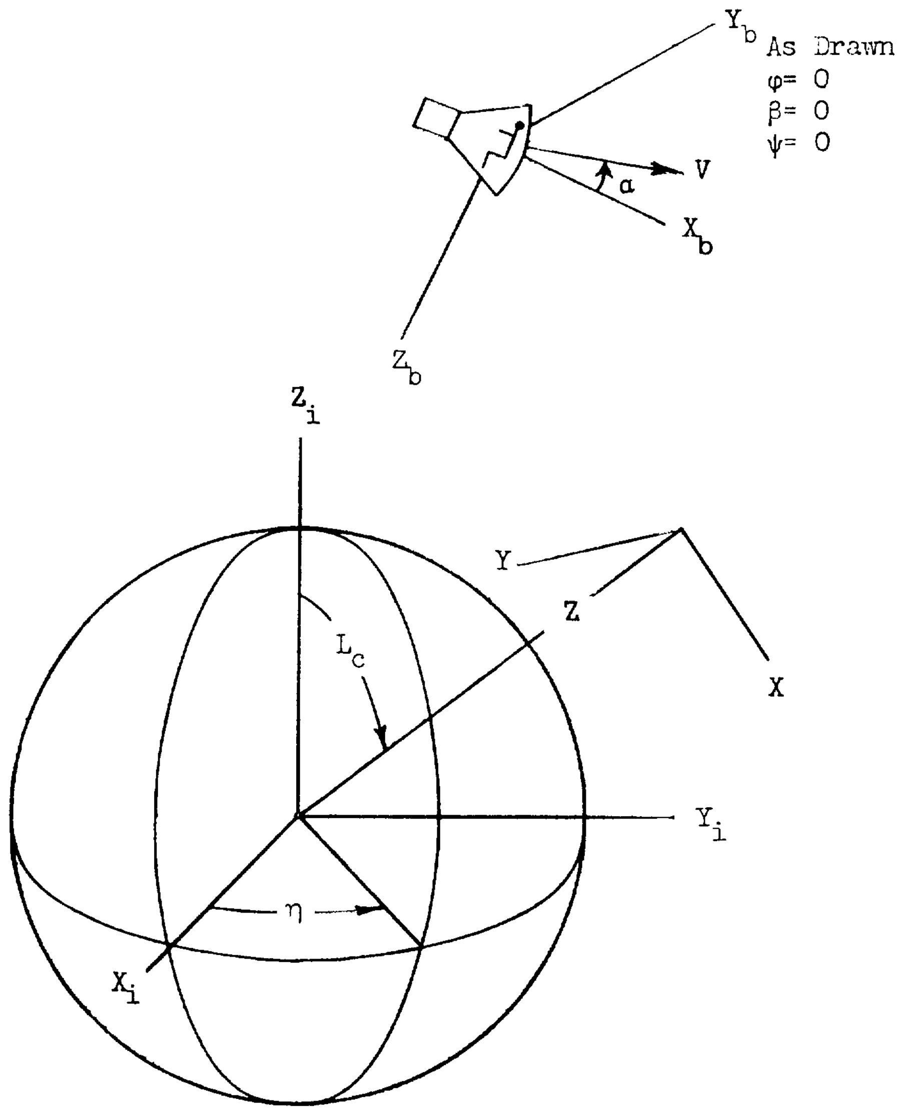


Figure 1.- Geometry of axis system.

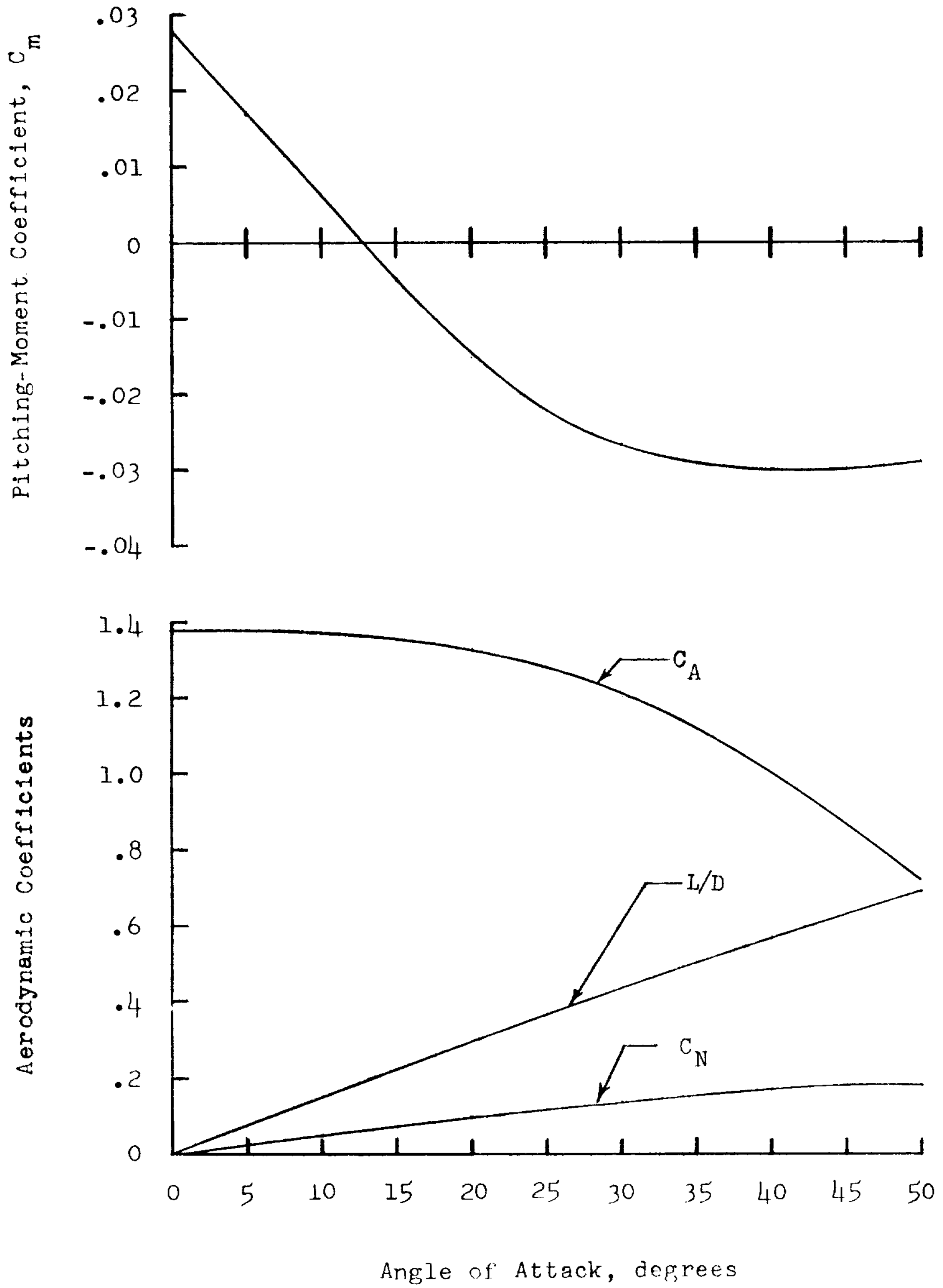


Figure 2.- Variation in aerodynamic coefficients for assumed vehicle.

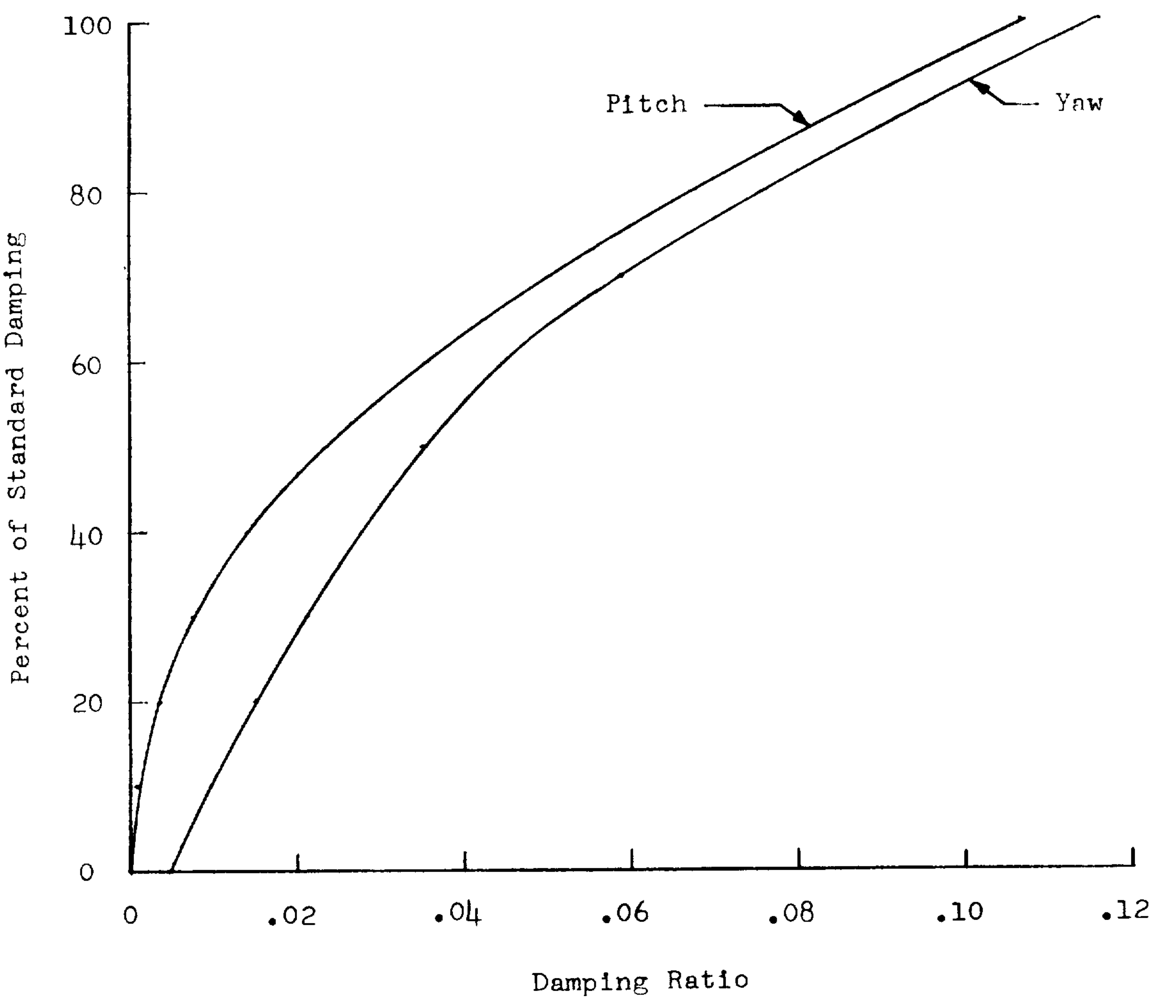


Figure 3.- Pitch and yaw reaction damping ratio at maximum dynamic pressure ($\bar{q}$ = 400 lb/sq ft) for different levels of applied damping.

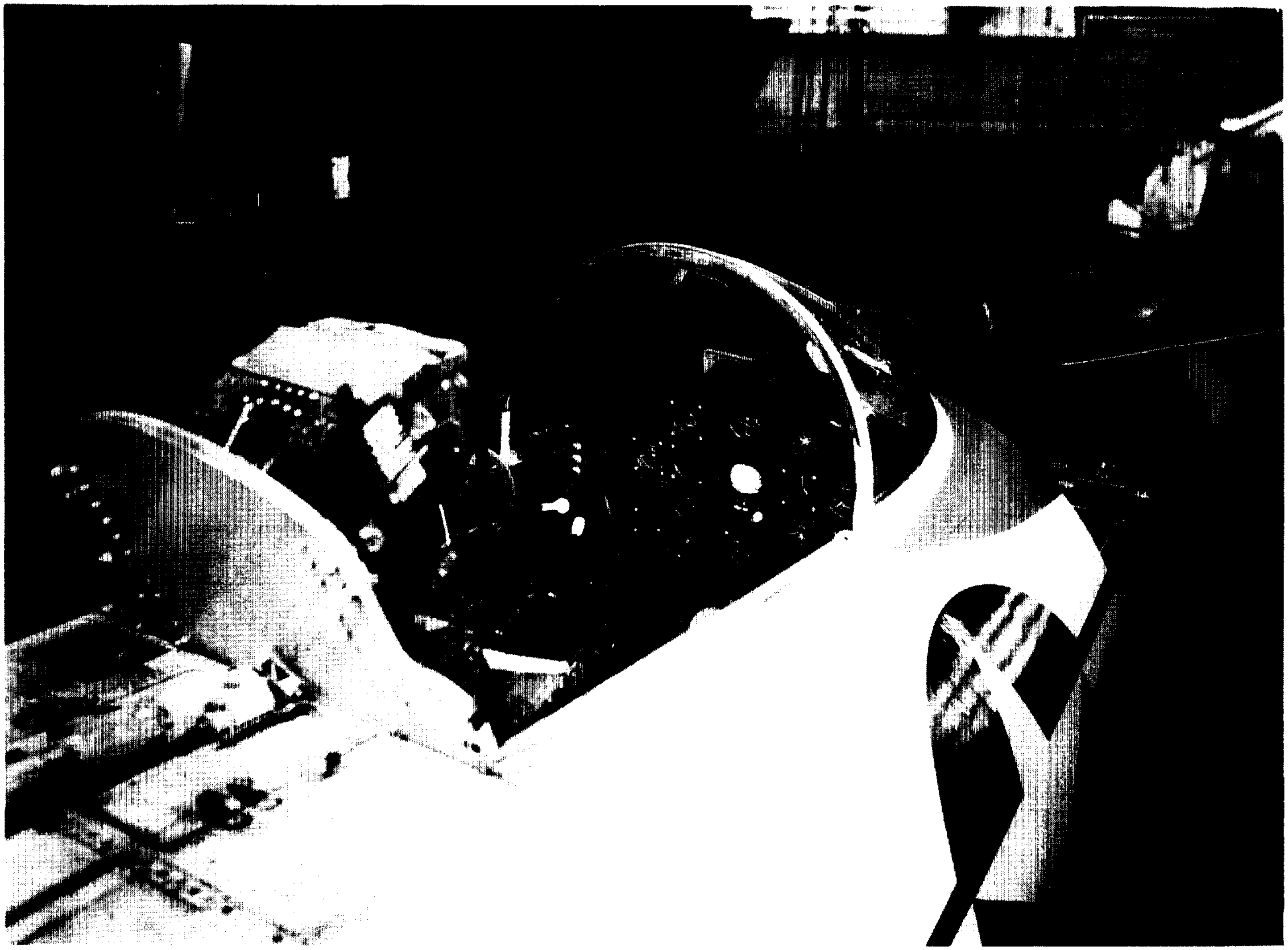


Figure 4.- Layout of simulated cockpit. L-61-3236

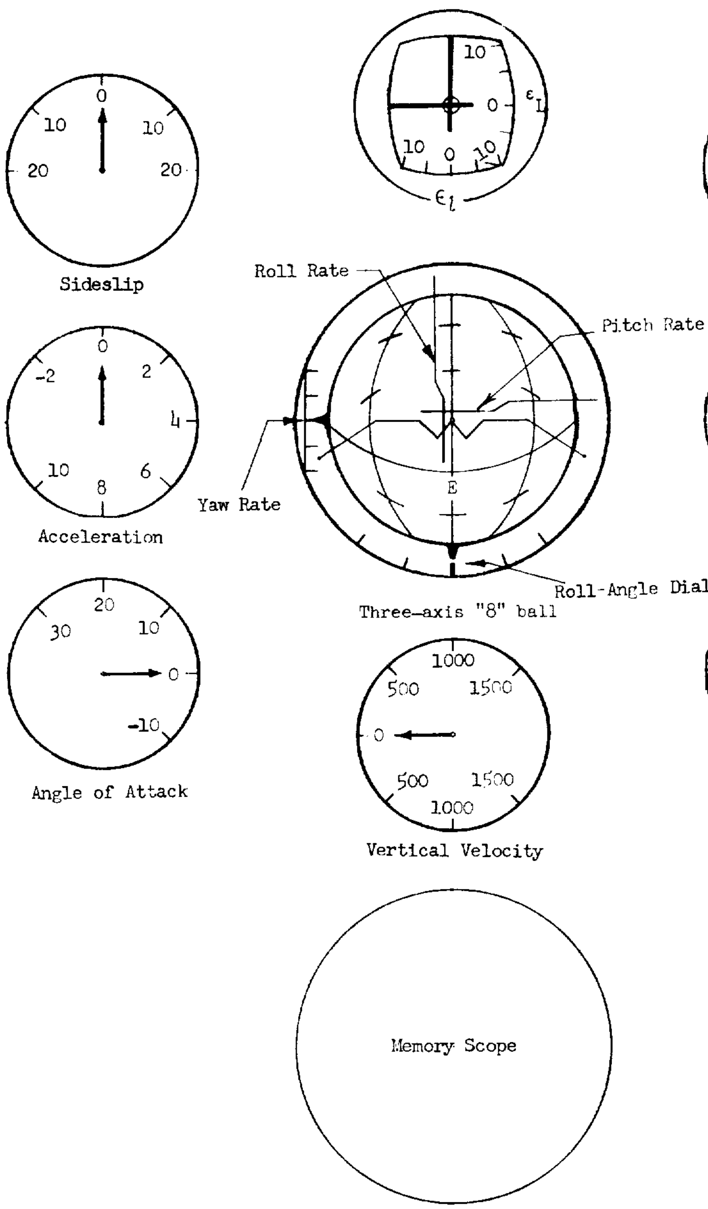
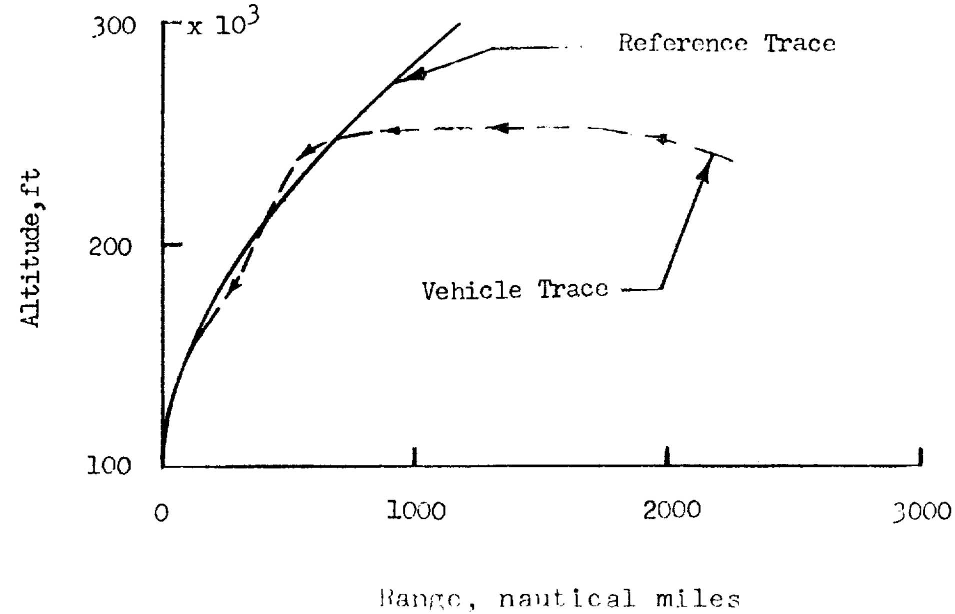
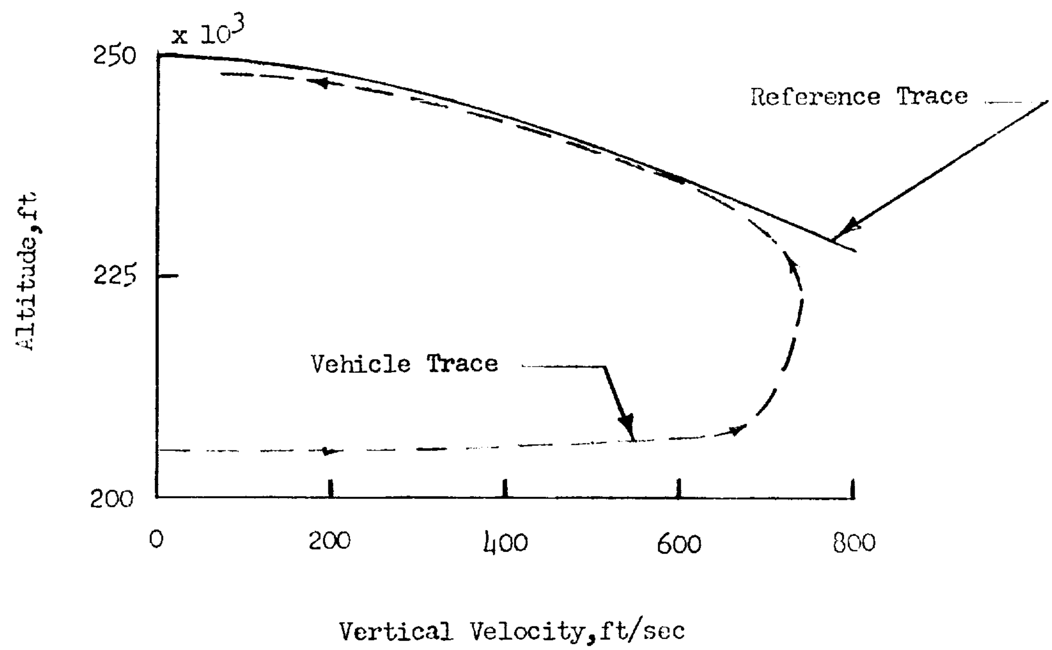


Figure 5.- Instrument panel used in simulation.

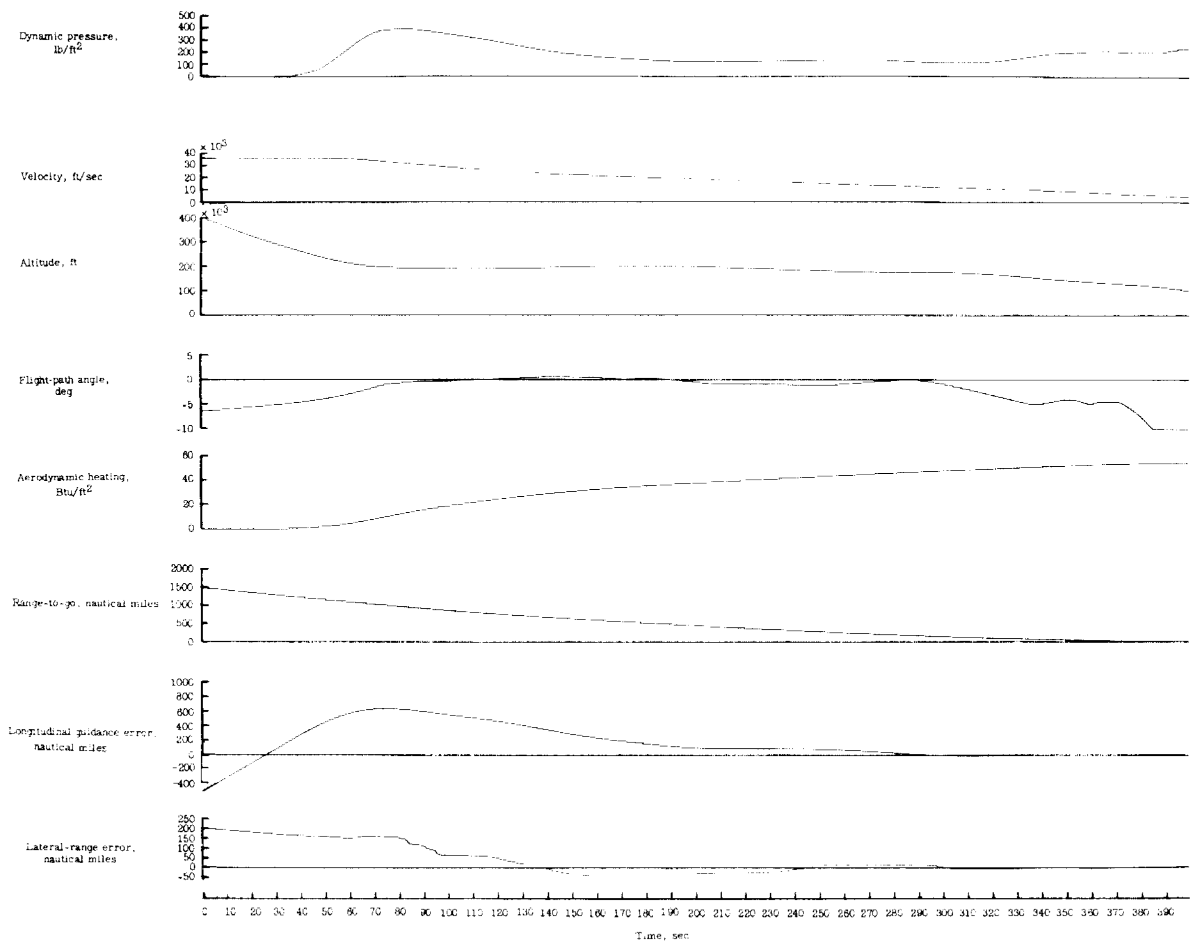


(a) Memory-scope display of range-to-go as a function of altitude.



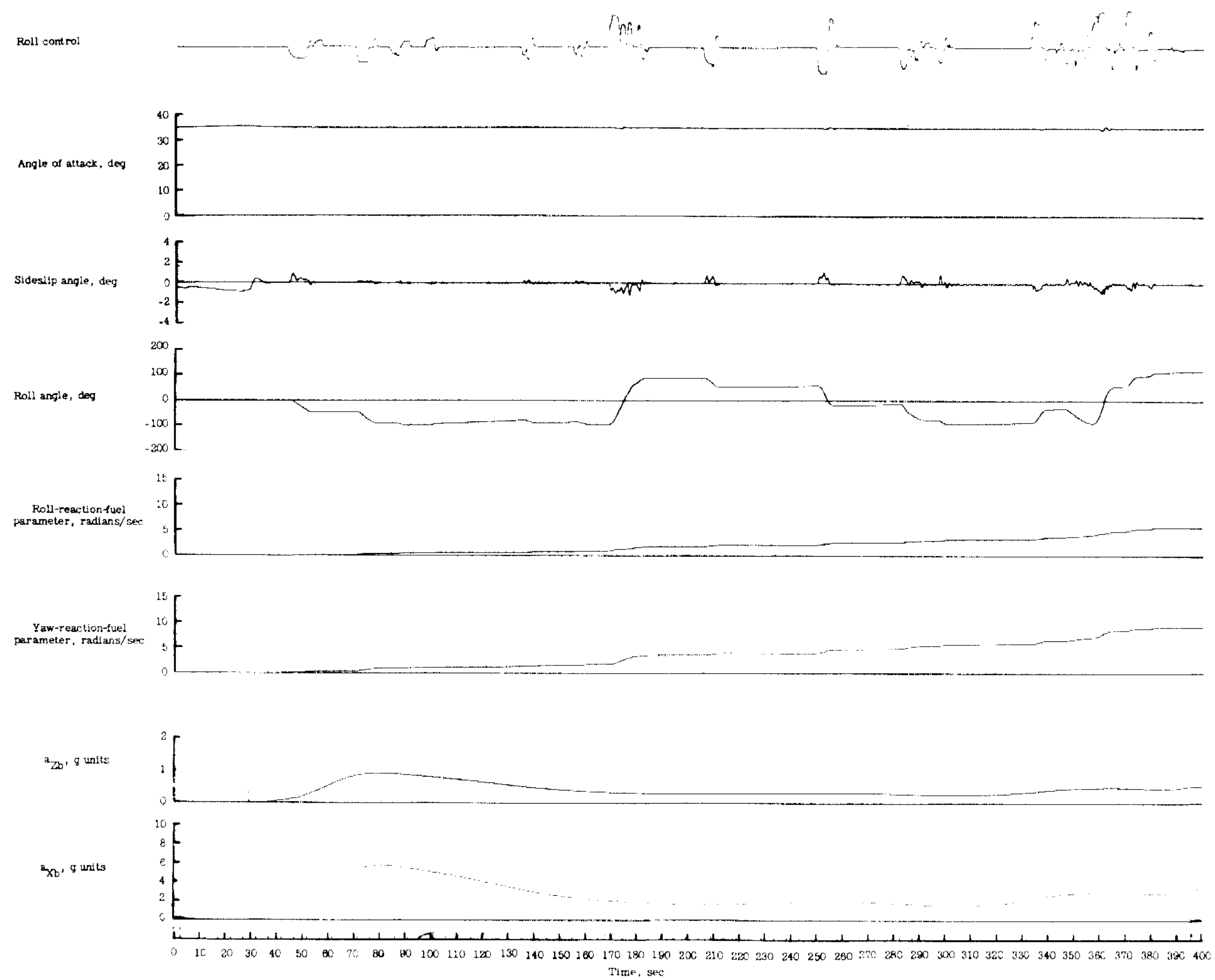
(b) Memory-scope display of vertical velocity as a function of altitude.

Figure 6.- Memory-scope displays.



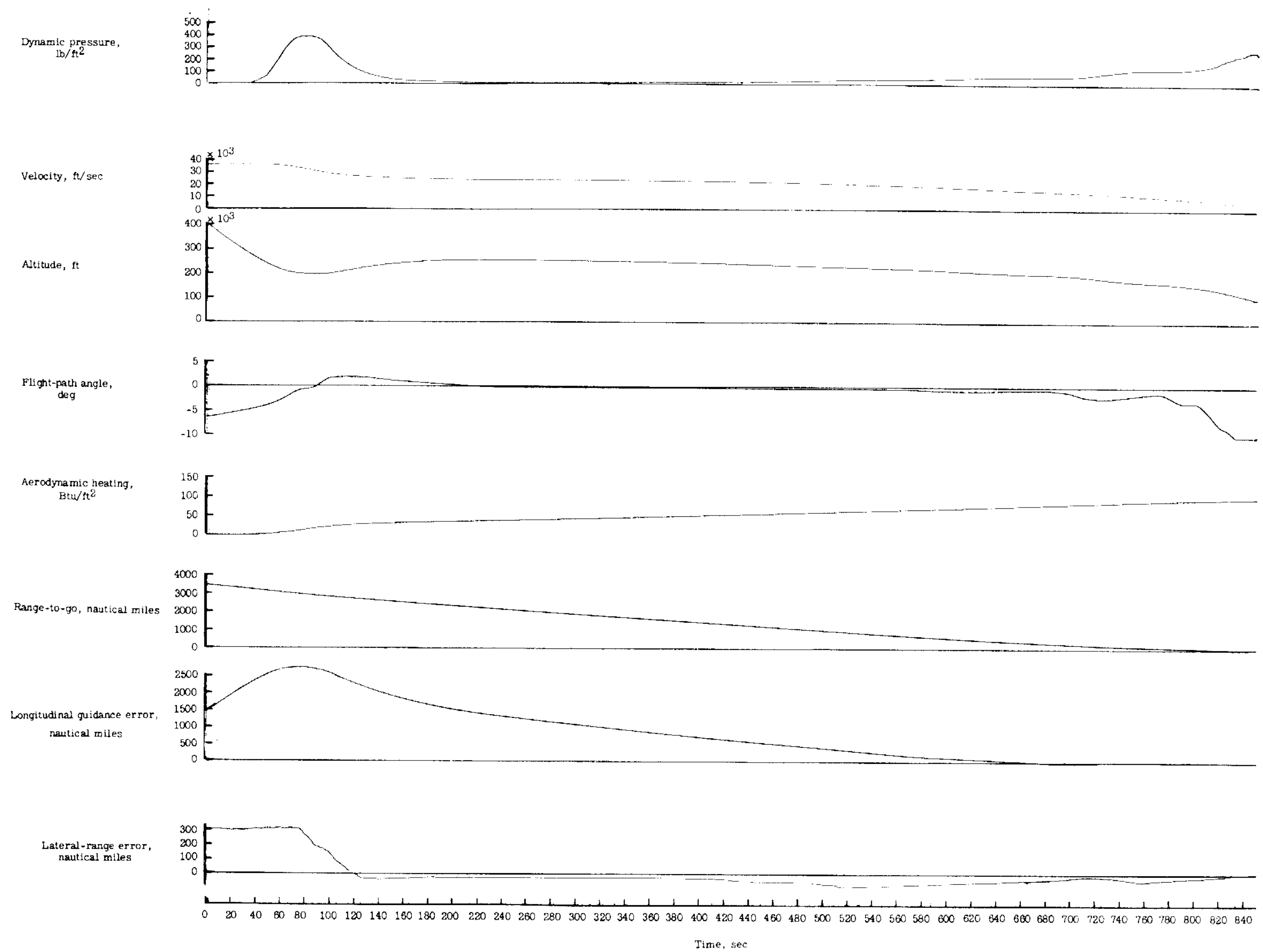
(a) Time histories for a short-range entry with a desired longitudinal range of 1,500 miles and a desired lateral range of 200 miles.

Figure 7.- Variation in trajectory variables for typical piloted entries. V_o = 36,000 ft/sec; h_o = 400,000 feet; γ_o = -6.5°.



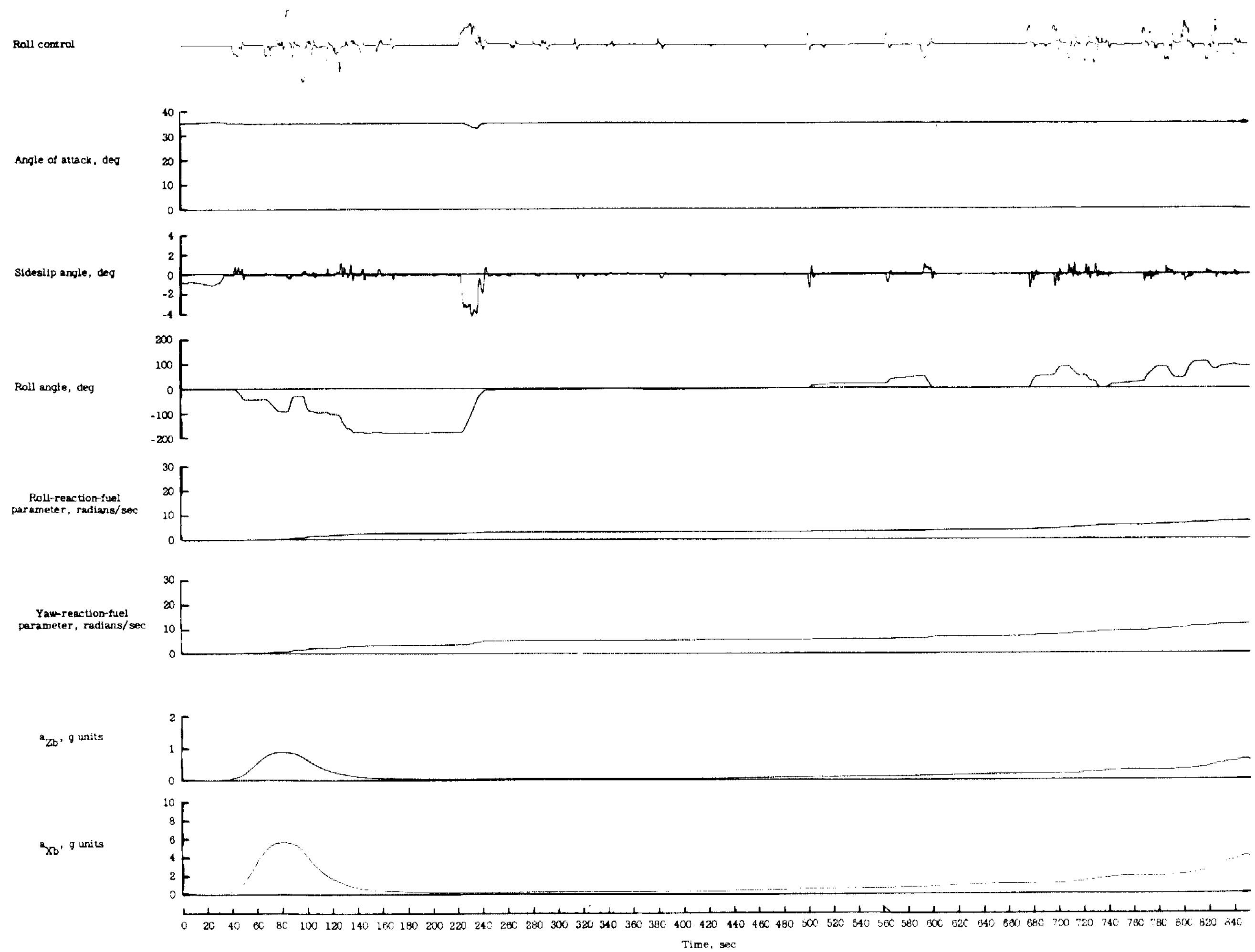
(a) Concluded.

Figure 7.- Continued.



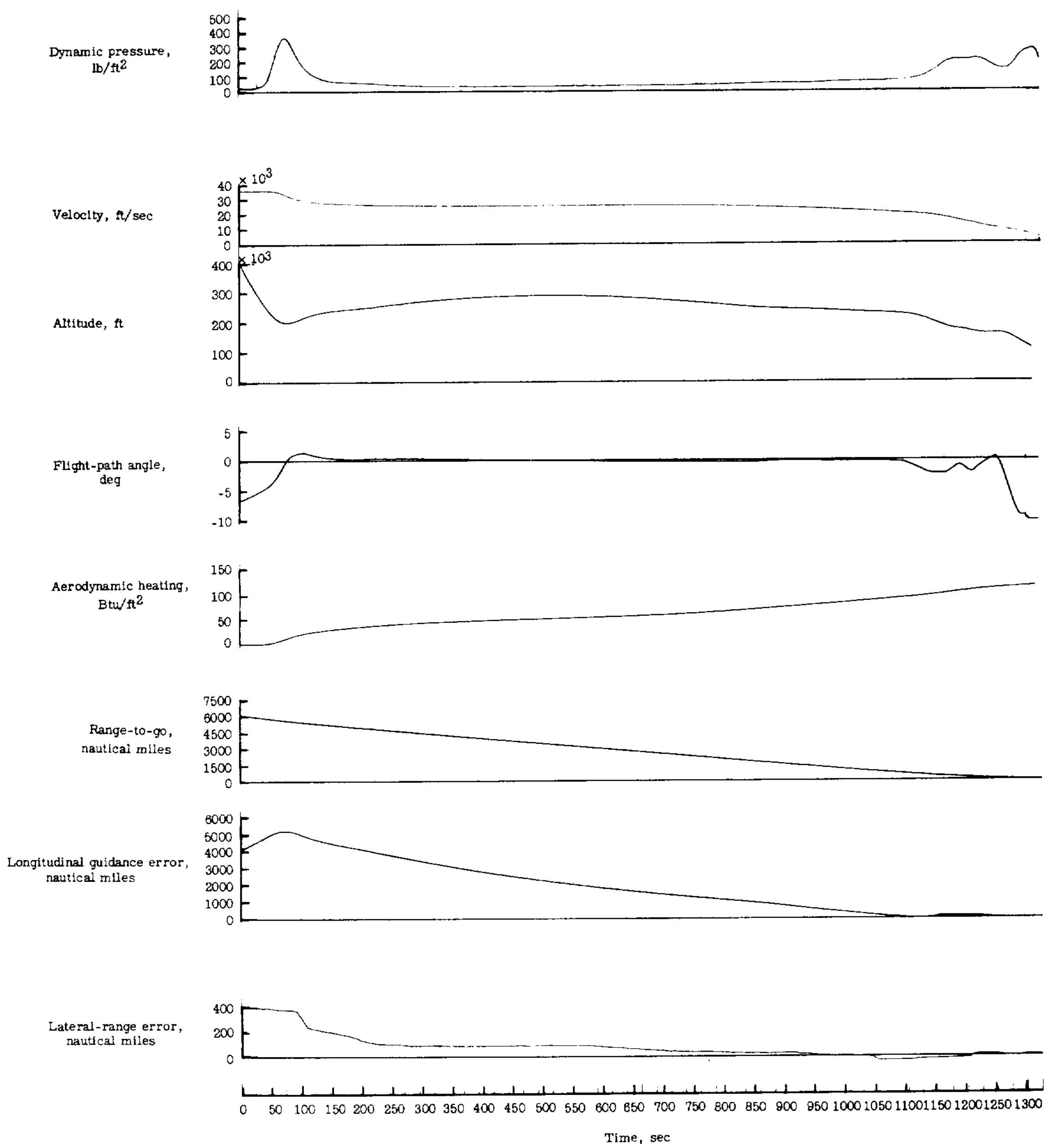
(b) Time histories of a medium-range entry with a desired longitudinal range of 3,500 miles and a desired lateral range of 300 miles.

Figure 7.- Continued.



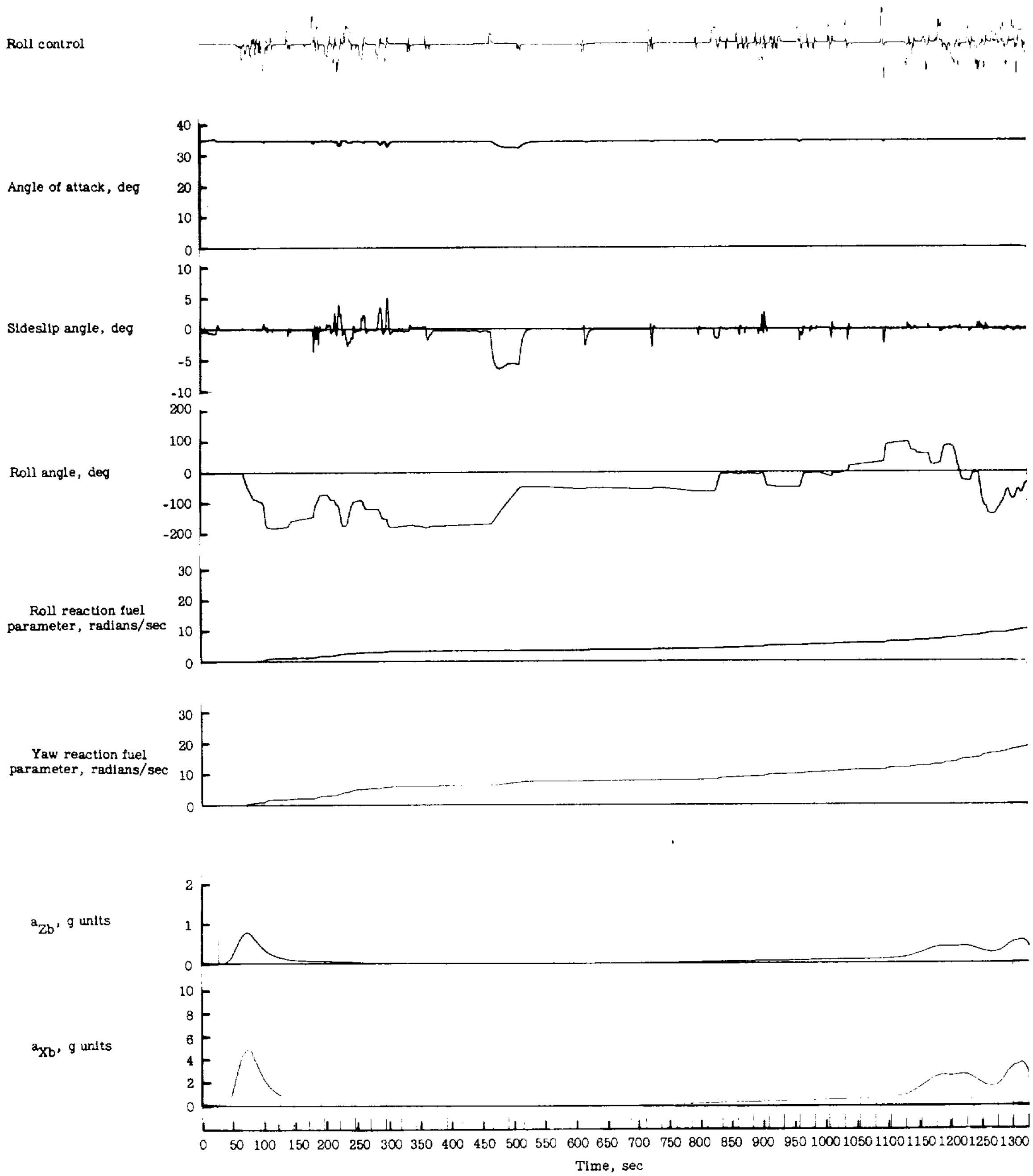
(b) Concluded.

Figure 7.- Continued.



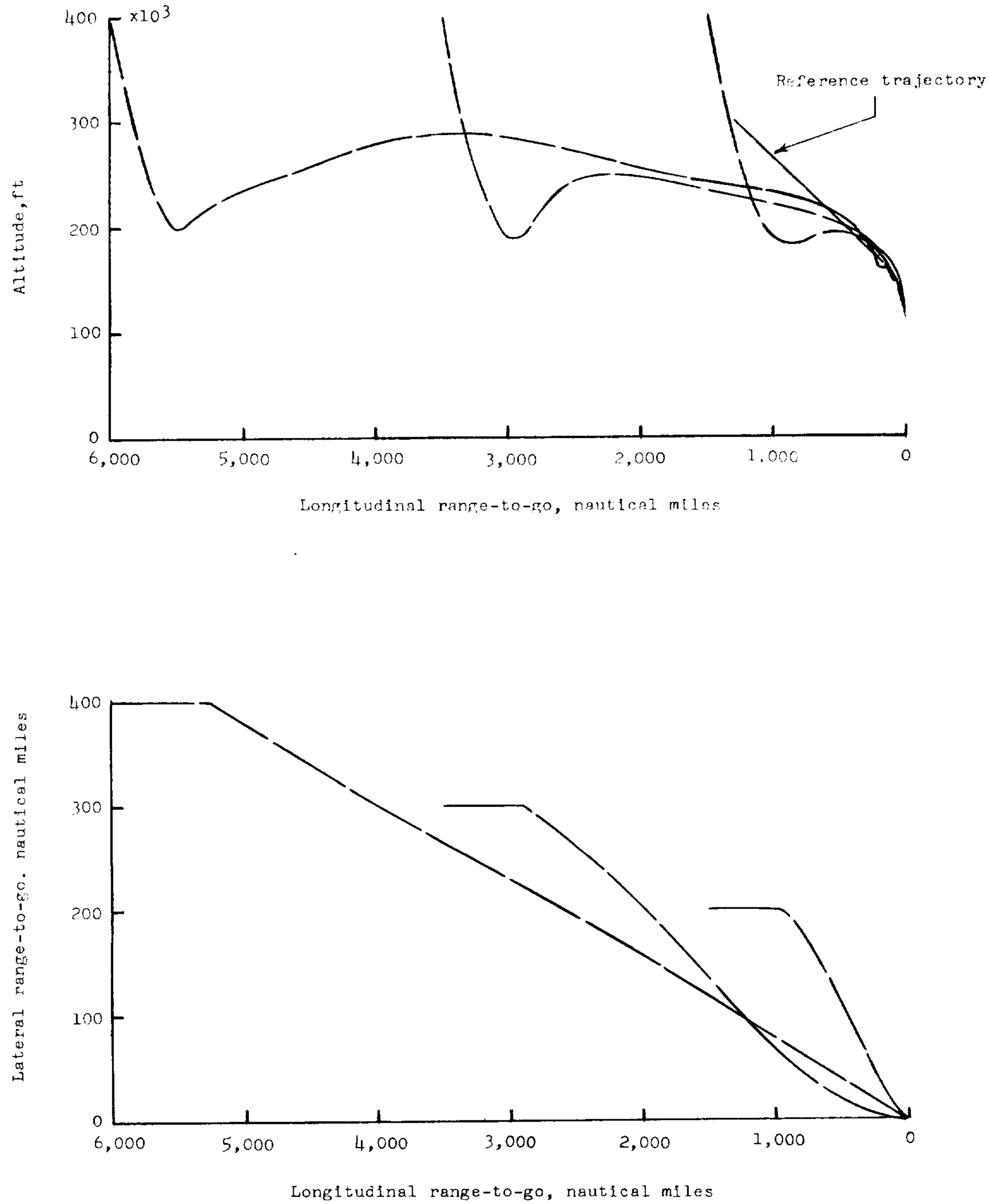
(c) Time histories for a long-range entry with a desired longitudinal range of 6,000 miles and a desired lateral range of 400 miles.

Figure 7.- Continued.



(c) Concluded.

Figure 7.- Continued.



(d) Variation in altitude and lateral range-to-go with longitudinal range-to-go for a short-range, medium-range, and long-range entry.

Figure 7.- Concluded.

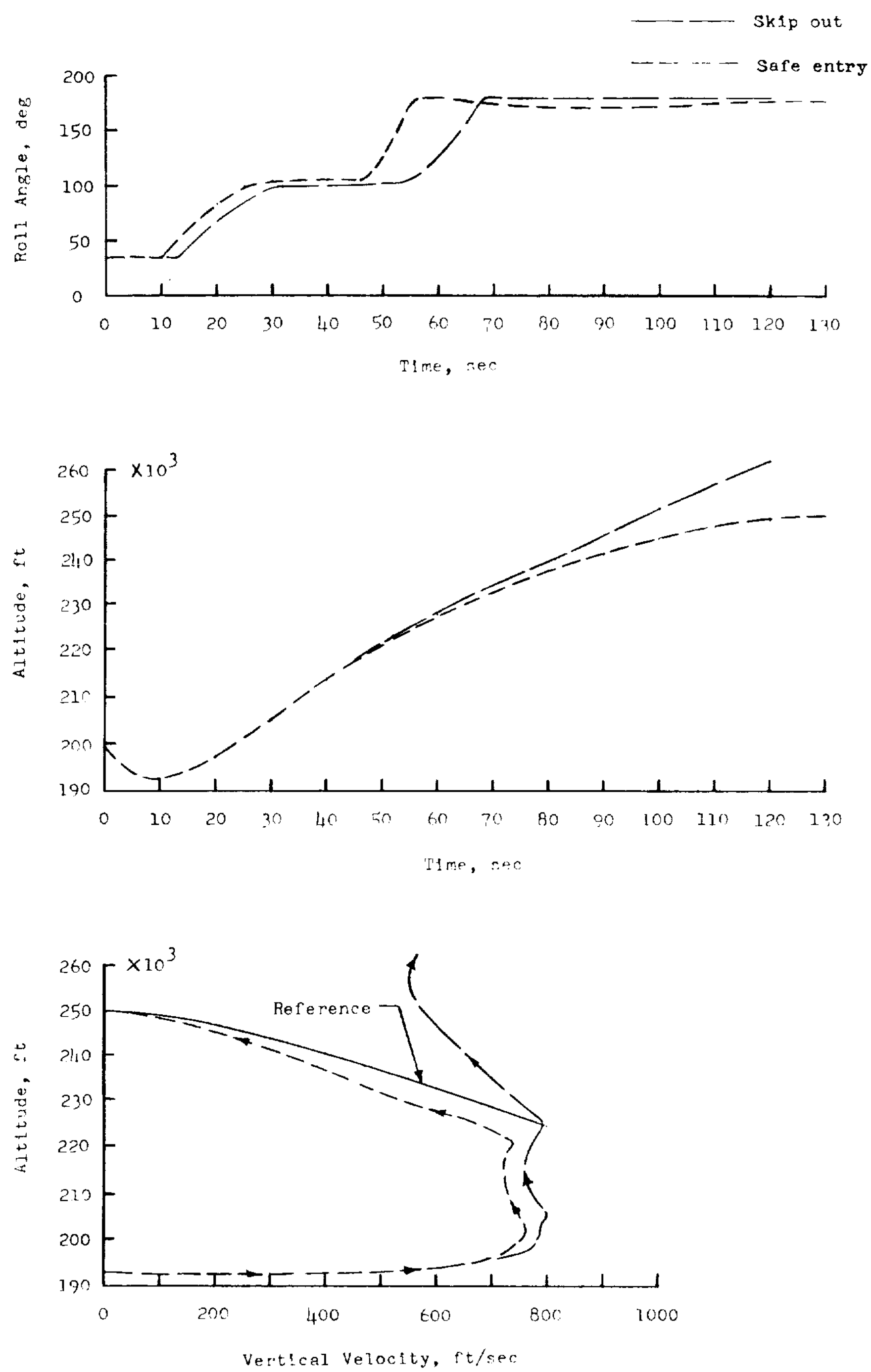


Figure 8.- Time histories of roll angle and altitude and the variation in vertical velocity with altitude illustrating the pull-up maneuver for typical long-range entries.

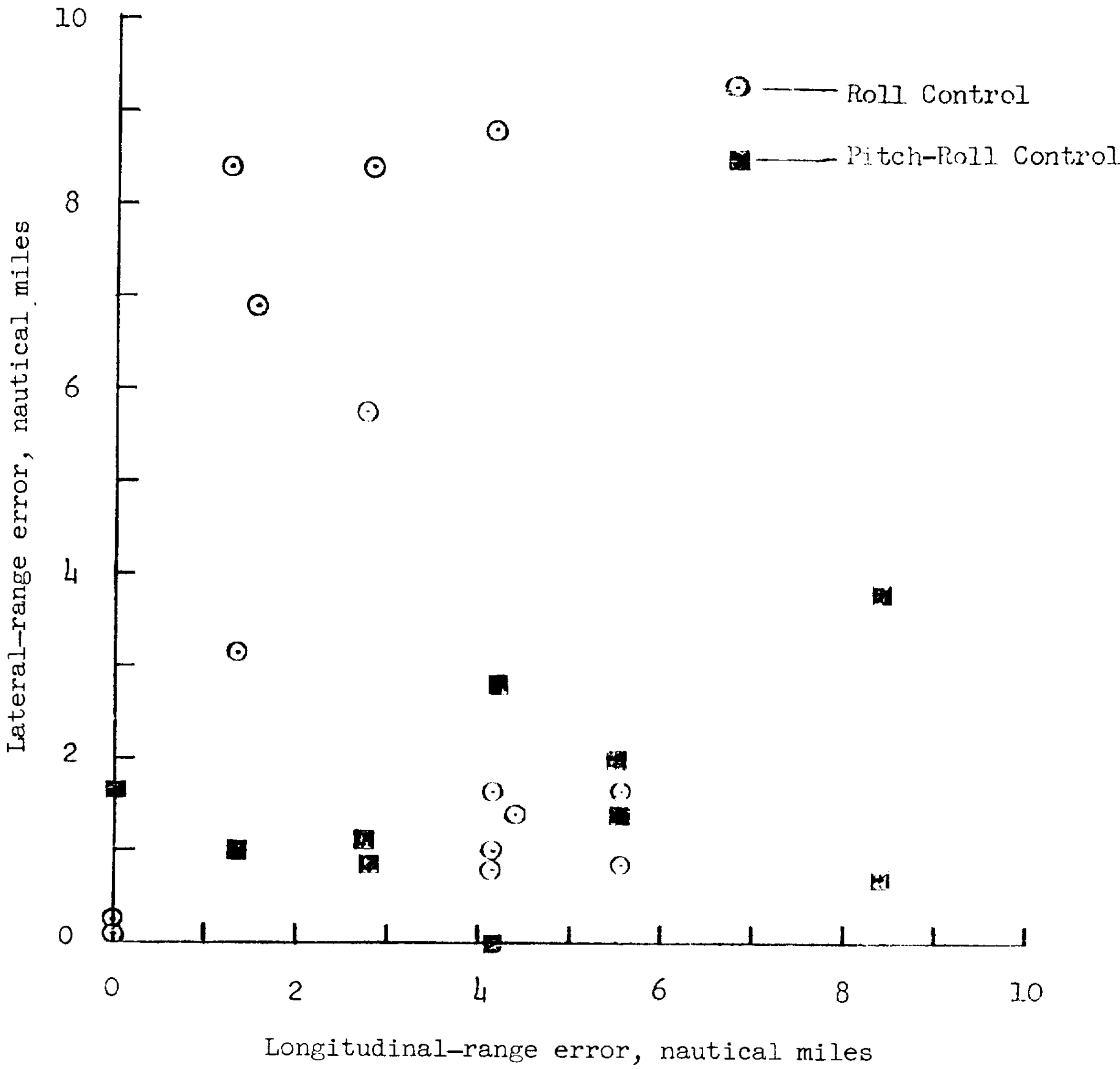


Figure 9.- Terminal errors in longitudinal and lateral ranges at an altitude of 100,000 feet for entries with pitch-roll and roll-only control.

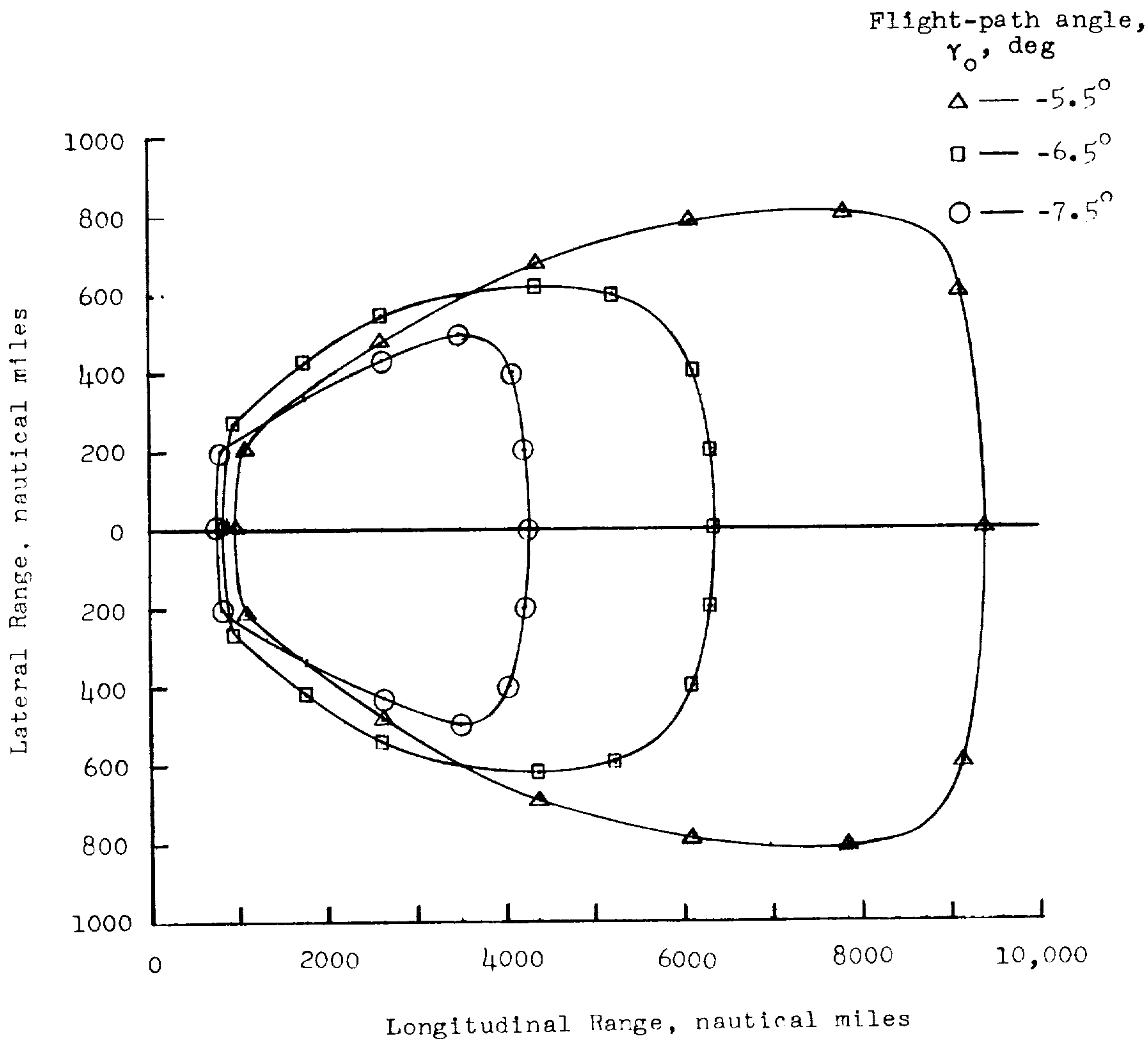


Figure 10.- Locus of end points of trajectories showing the maximum longitudinal and lateral ranges obtainable for piloted entries with different flight-path angles. V_o = 36,000 ft/sec; h_o = 400,000 feet.

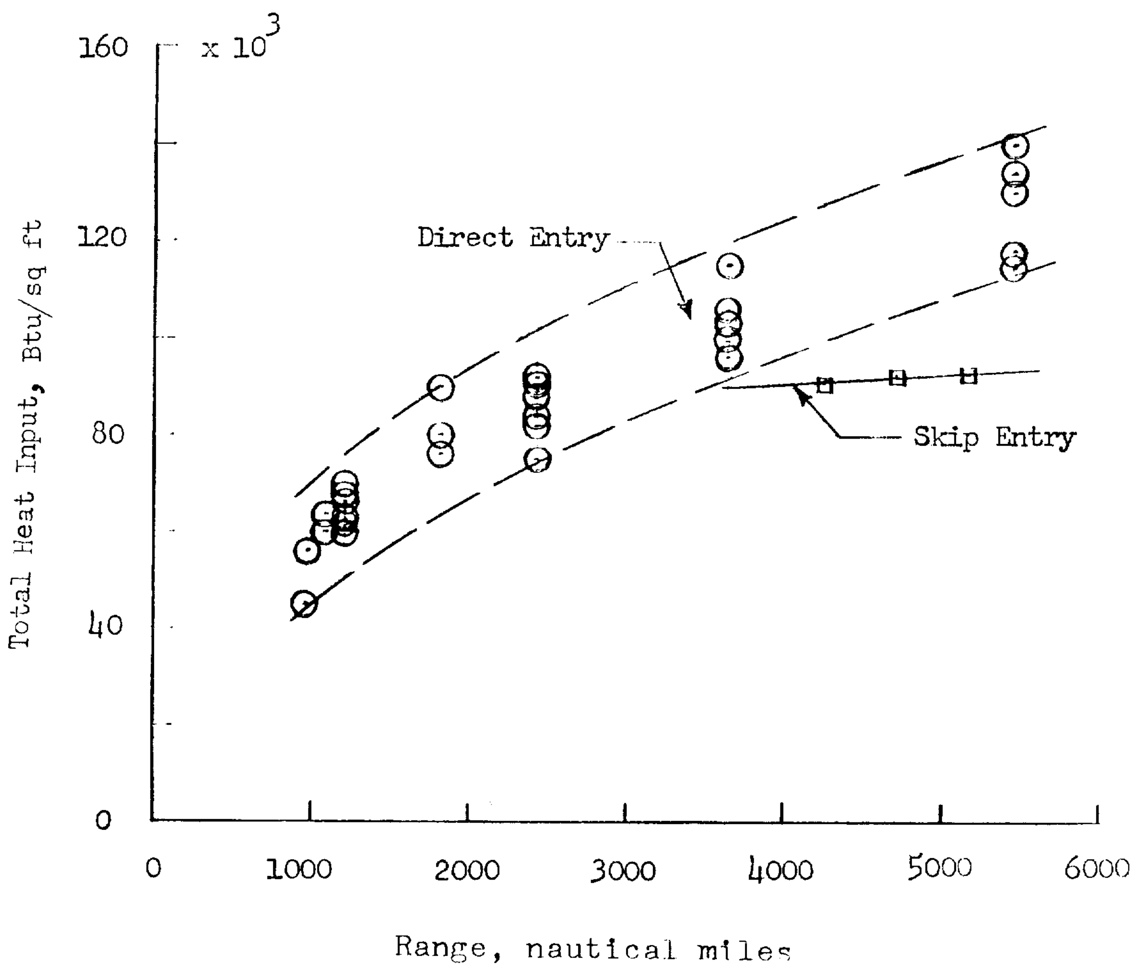
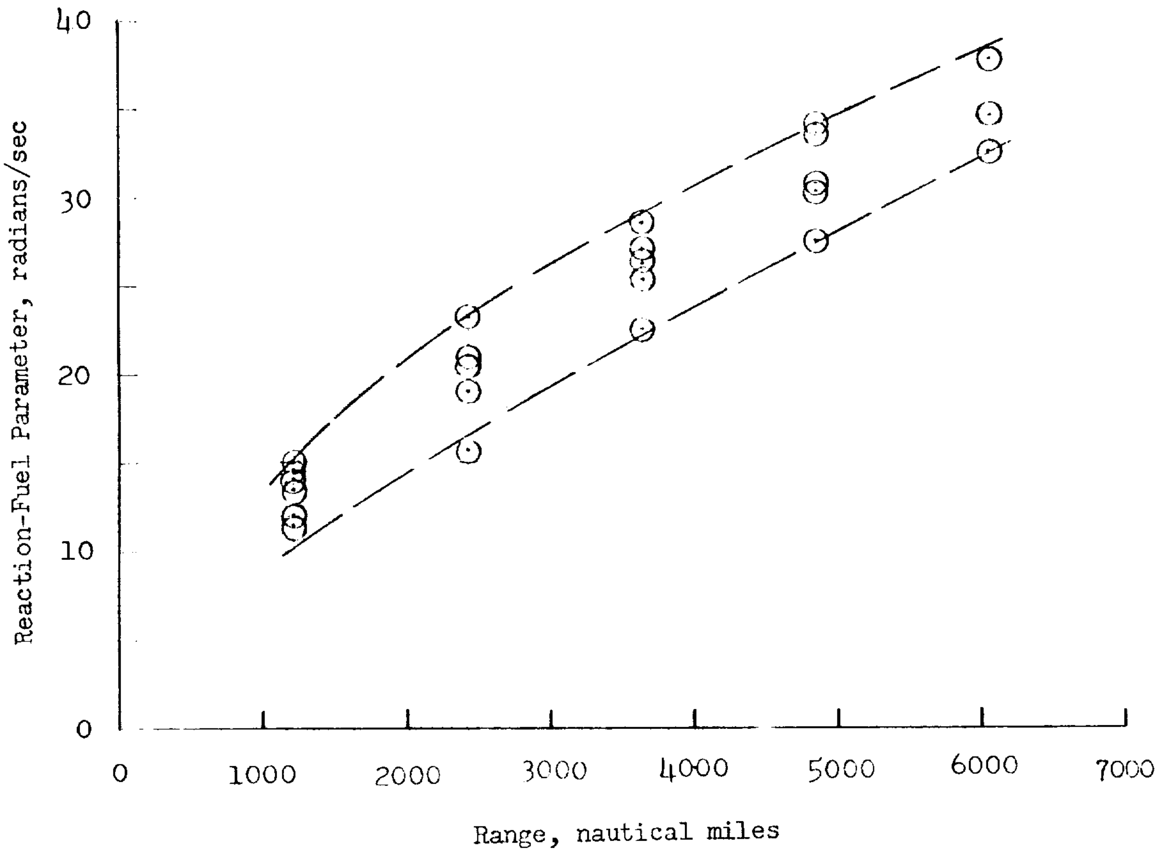
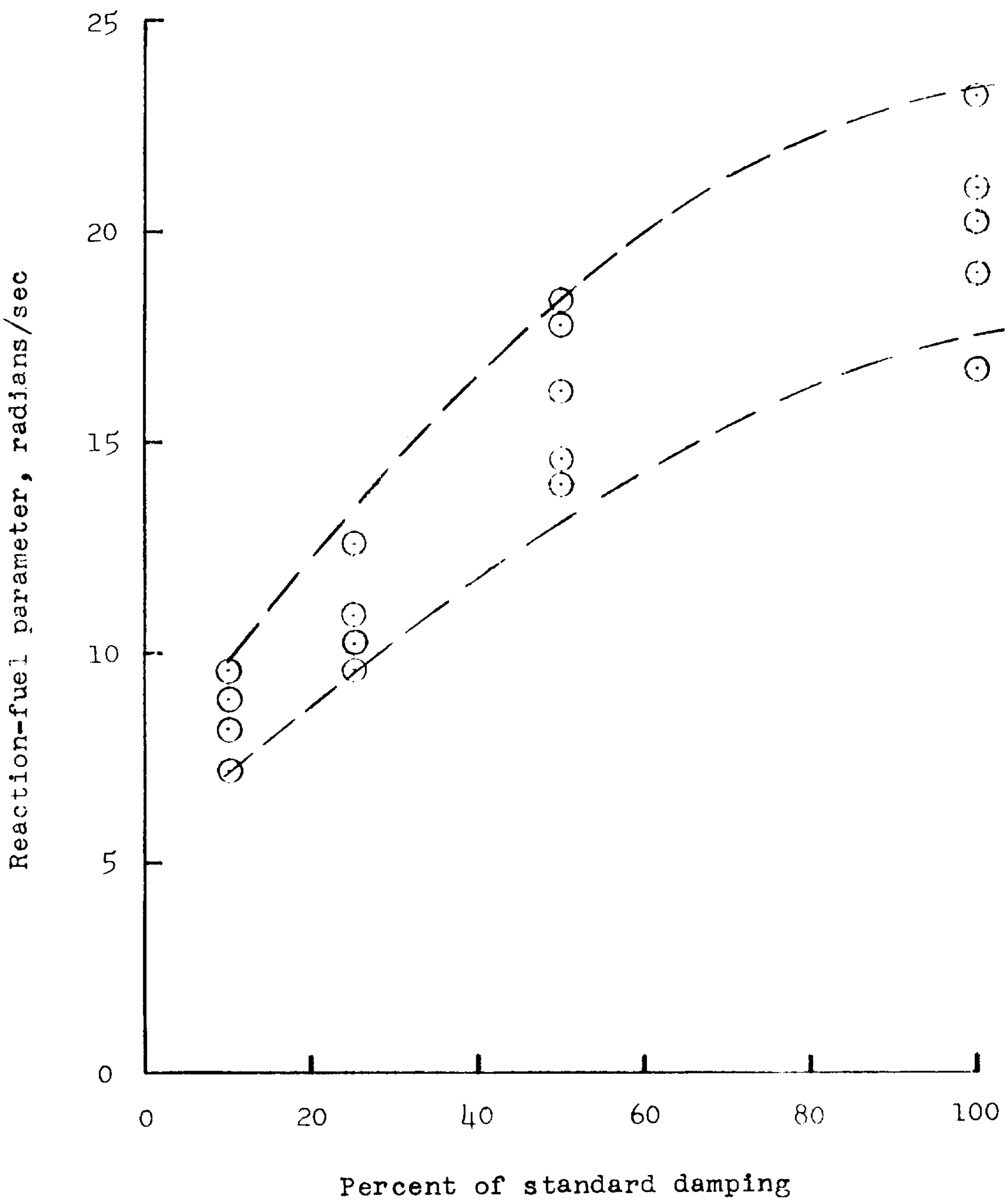


Figure 11.- Variation in aerodynamic heat input with range for direct and skip entries. V_o = 36,000 ft/sec; h_o = 400,000 feet; $\gamma_o = -6.5^o$.



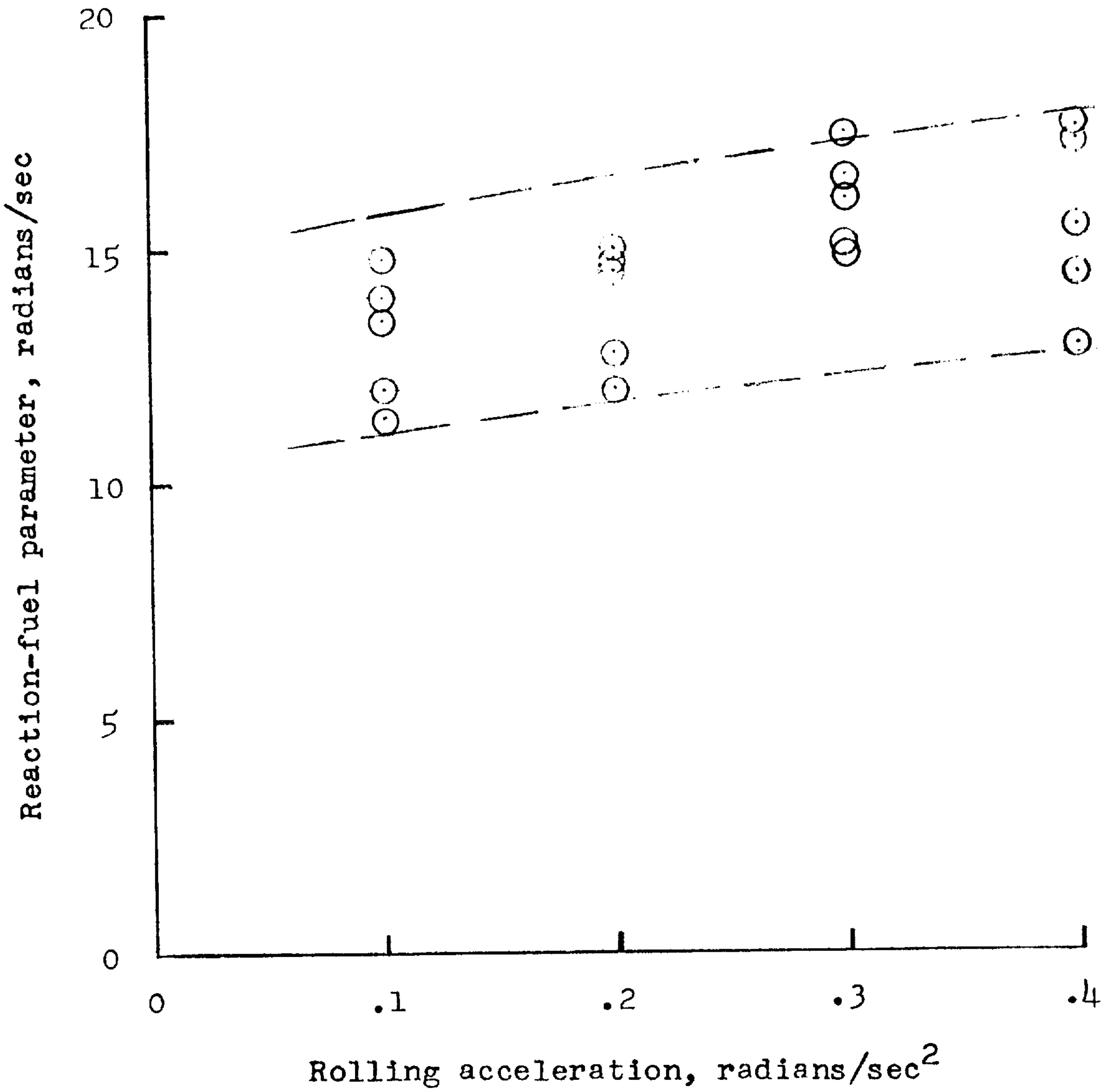
(a) Variation in reaction-fuel parameter with range.

Figure 12.- Variation in the reaction-fuel parameter with range, damping, and rolling acceleration for piloted entries. V_o = 36,000 ft/sec; h_o = 400,000 feet; γ_o = -6.5°.



(b) Variation in reaction-fuel parameter with artificial damping applied about the pitch and yaw axes for entries with a desired range of 2,800 miles.

Figure 12.- Continued.



(c) Variation in reaction-fuel parameter with rolling acceleration for entries with a desired range of 1,400 miles.

Figure 12.- Concluded.